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THE PERMO-CARBONIFEROUS OF NORTHERN NEW MEXICO

S. W. WILLISTON
The University of Chicago

E. C. CASE
The University of Michigan

The age of the Red Beds of the Rocky Mountain region has long been in doubt. They outcrop extensively along the eastern foothills, extending across Wyoming from the Laramie Mountains to the Wind River Range, thence through eastern Utah and western Colorado, with extensive exposures in the southwestern part of that state; in various places in northern New Mexico, from the San Juan region east; southwestward in the Ft. Wingate region; and along the eastern part of the same state. On the plains are extensive outcroppings in southwestern Kansas, thence across Oklahoma into the northern and western parts of Texas. Vertebrate fossils of Triassic age have been reported from the Lander region (Williston, Branson), Como and Red Mt. (Reed and Williston) in Wyoming; from northeastern Utah (Lucas); western Colorado (Cross); northern New Mexico (Cope); Fort Wingate, New Mexico (Yale collections, Shufeldt); Pan Handle (Cope), and Claremont, Texas (Brown). The fossils, consisting chiefly of phytosaurs and labyrinthodonts, agree, for the most part, so closely with those of the Keuper of Europe that their horizon may be confidently fixed as Upper Trias. Below the horizon yielding

these remains there are rocks of about nine hundred feet in thickness in the Lander region, and perhaps more in the southern region, which have been hitherto supposed to be utterly barren of all fossils, whether vertebrate or invertebrate; and there are at least three hundred and fifty feet immediately underlying strata of certain Upper Trias age which have never, in any place, yielded fossils.

Everywhere characteristic of the uppermost beds, from Lander to New Mexico, Kansas, and Texas, are from five hundred to possibly a thousand feet, as estimated, of barren or almost barren measures, characterized by the lighter colors of the sandstones, often of aeolian origin, and more or less interspersed or capped with massive beds of gypsum, as at Lander, in Kansas, Texas, and New Mexico. The age of these upper beds throughout is assumed to be Triassic, but we know of no evidence whatever, save the color of the rocks, to differentiate the uppermost of them from the Jurassic,[1] which lie in some places quite conformably above them. At Cañon City, Colo., the Hallopus beds, lying conformably immediately above the Red Beds, have been supposed by Marsh to be either of Lower Jurassic or Upper Triassic age, and the senior author from an examination of them agrees quite with his opinion. With this possible exception there are no fresh-water deposits in North America of Lower Jurassic age, the beds lying immediately above the Red Beds, whether conformably or not, being either the marine Jurassic (Sundance), or Morrison of uppermost Jurassic or lowermost Cretaceous age.

At the base of these barren measures of Upper Trias or Jura-Trias age, in the Lander region, are thirty or more feet of massive sandstones, red, whitish, or variegated in color, underlain by pebbly conglomerates and clays, in which occur the remains of vertebrate fossils, if not in the sandstones themselves. Below these fossiliferous beds, in this region, are nine hundred feet of red sandstones and clays, as recently accurately determined by Branson (*in lit.*) lying conformably, both with the overlying Upper Trias sandstones and the underlying beds of Pennsylvanian age (Embar beds, Branson), in which no fossils of any kind have ever been detected, though

[1] These measures were referred by Cope to the Jurassic many years ago (G. M. Wheeler, *Annual Report*, 1875, pp. 78 ff.).

we are of the opinion that careful, persistent search in the lower two or three hundred feet will be rewarded with vertebrate remains. In Kansas the Red Beds have been estimated to be one thousand feet in thickness and said to be utterly unfossiliferous, by Cragin

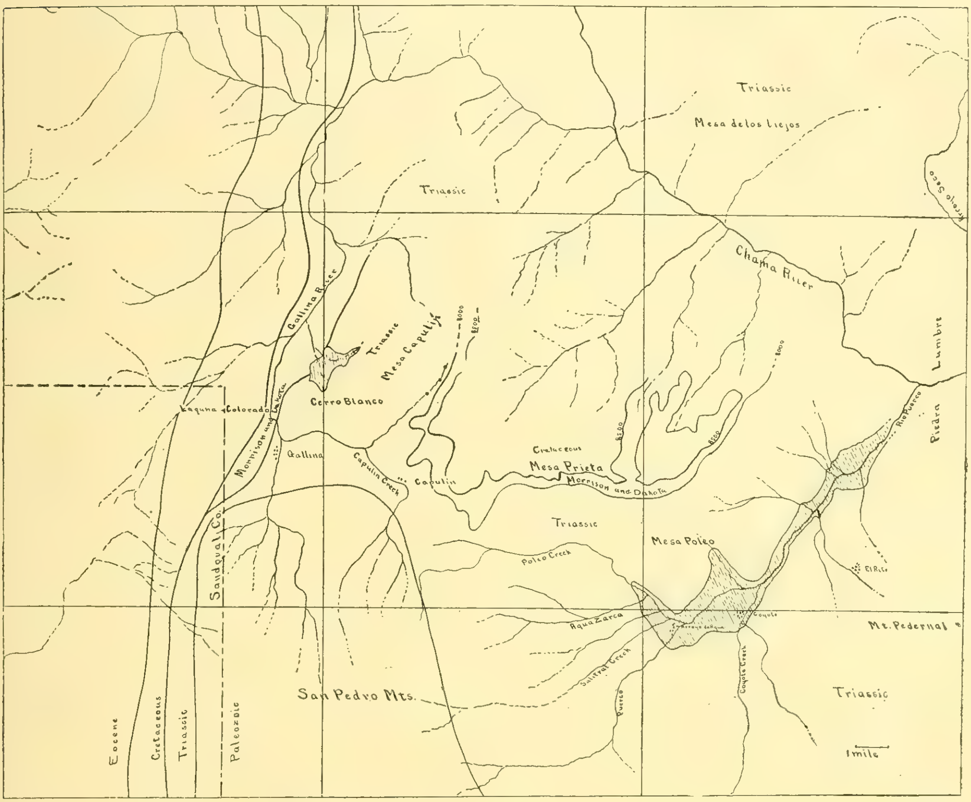

FIG. 1.—Map of Mesa Prieta and adjoining country. The fossiliferous Permo-Carboniferous is shown in the areas indicated by broken lines. Comparison with the Jemez topographic sheet will make details evident.

and Hay. From just south of the Kansas line Professor Gould some years ago obtained very typical remains of the amphibian *Eryops* (*E. Willistoni* Moodie), a characteristic "Permian" fossil, and it is very probable that intelligent search will show, somewhere between this horizon and the barren beds of southern Kansas, the

characteristic massive sandstones and phytosaur remains, more probably so since such fossils have been actually found not far to the west.

Cross has reported unconformity of the Red Beds in western Colorado, but it has been our experience, wherever we have examined them, that they lie conformably throughout, so far as stratigraphical evidence indicates. In Kansas, Oklahoma, Texas, and eastern New Mexico they seem to be thicker, perhaps reaching two thousand feet in their totality. In northern New Mexico our observations the present year give a thickness of not over sixteen hundred feet, while in the Lander region their total thickness is fourteen hundred and forty feet, as recently accurately determined by Professor Branson.

More than thirty years ago, the late David A. Baldwin collected from the Red Beds of northern New Mexico, which he considered of Triassic age throughout, considerable quantities of vertebrate fossils, the most of which are now preserved in the museum of Yale University, and the remainder in the American Museum of New York City. At the time of their collection two or three very brief descriptive papers, referring them to the Permian, were published by the late Professors Marsh and Cope, but without giving any further information as to the locality of their origin than simply New Mexico. Within the past few years the present writers have published further notes and descriptions of the remains in these collections, with more definite information of their occurrence. With more precise information kindly given by Professor Schuchert an expedition was planned to explore the region the past summer. This expedition, composed of Mr. Paul Miller of the University of Chicago and the present writers, entered the field the early part of July from Espanola, near the mouth of the Chama River, with Abiquiu as the chief base of supplies. Dr. v. Huene was a member of the party for three weeks. Abiquiu, one of the oldest settlements in the United States, is located twenty-seven miles northwest of Espanola on the Chama. It is our pleasure to acknowledge with gratitude the kind favors shown us here by Mr. Henry Grant.

From Abiquiu our entrance into the Red Beds was made in the

famous cañon known as El Cobre, so named because of the indications (indications only) of copper long known there. From thence the expedition followed the valley of the Puerco to the embouchure of its chief tributary, the Poleo (Arroya de Agua). Later a brief trip was made to the valley of the Gallina, and as far west as the Wasatch deposits in Sandoval County.

From Espanola to Abiquiu the road follows the sandy valley of the Chama, bordered by Tertiary deposits, coarse white sandstones, often eroded into typical badland forms, and leading up to lava-capped table-lands. Three or four miles west of Abiquiu the Tertiary sandstones lie immediately upon heavy beds of red clays and red sandstones of Triassic age. In the immediate stream bed

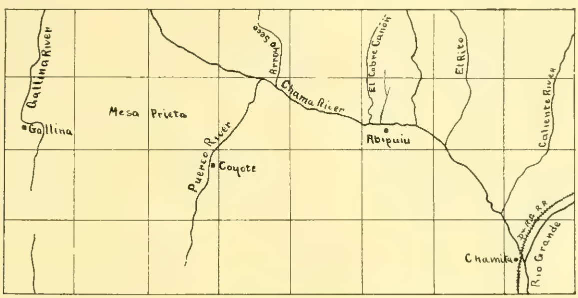

FIG. 2.—Map of region about Abiquiu showing location of El Cobre Cañon

of the Cobre creek we observed conglomerates twenty or more feet in thickness, composed of quartzite bowlders reaching six or eight inches in diameter, and almost devoid of binding matrix. Farther northwest and toward the entrance into the Cobre basin there are fifty or more feet of red and variegated clays, which in turn are underlain by from fifty to seventy-five feet of more massive sandstones, with a more or less persistent conglomerate pebbly layer beneath them, yielding phytosaur remains. It is through these sandstones that the outlet of the basin occurs in a narrow but not deep gorge.

El Cobre Cañon or basin is formed by the erosion of an unsymmetrical dome-shaped anticline more or less faulted on the northeastern and southeastern sides, the brim formed everywhere by the massive sandstones of basal Upper Triassic age, the strata sloping

in all directions, but chiefly east and west. The basin thus formed is about two and a half miles in its greatest extent, in a north-and-south direction. Its very steep walls, for the most part about seven hundred feet in altitude, attain their greatest height in the north-west part, where the altitude may exceed eight hundred feet, and where the Permian exposures are the greatest.

The erosion of the floor of this basin, acting on the beds of alternating sandstones and clays, has formed a series of steps or low cliffs, which for the most part dip at a small angle toward the west. Toward the sides and upper end of the cañon these ridges become more prominent, frequently forming high bluffs and cliffs. The lowermost beds in the cañon are deep chocolate-colored sandstones and fine conglomerates; the latter weather into low, rounded hills, frequently streaked with greenish layers. Bone fragments were found in these layers in various places in the basin. Above these darker colored sandstones are more massive sandstones, weathering more or less whitish, which ascend at the north end of the cañon to perhaps three hundred and fifty feet above the stream bed. All vertebrate fossils that we found, of Permian age, were below these sandstones, which form a fairly definite horizon about the basin, and which may be taken as the lower limits of the Trias.

It has been questioned by us elsewhere whether the vertebrate fossils found in Texas, Oklahoma, southern Kansas, Illinois, and Pennsylvania are really of Permian age. At the south side of the cañon, the junior author found a perfect cast of a *Spirifer*, identified by Professor Schuchert as *S. rockymontanus* Marcou, a form occurring in Colorado in the Pennsylvanian. Though the specimen was found free, so that its exact horizon could not be determined, its excellent preservation proves conclusively that it had not been carried far from its original bed, and inasmuch as vertebrate fossils are found in the deepest strata of the cañon it seems quite certain that the specimen came from an intercalated bed among those yielding so-called Permian vertebrates. No other explanation seems possible. It is the conviction of both the present authors that the lowermost at least of the strata yielding vertebrate fossils are of Pennsylvanian age, and this conviction is strengthened by the known position of the vertebrate horizons in Texas, Kansas,

Illinois, and Pennsylvania, that of the last-named region definitely known to be Pennsylvanian.

Below is given a section (Section I) of the west wall of the Cobre Cañon as far down as the horizons yielding fossils of paleozoic age. It must be especially remembered, however, that this, as

SECTION I

EL COBRE

Yellow sandstone and conglomerates	75	Upper Trias	
Purplish and gray clays	40	"	
Purplish sandstones	20	Lower Trias?	Barren
Purplish clays and nodular sandstone	25	"	"
Red sandstone	5	"	"
Bright red clay	35	"	"
Purple clay	12	"	"
Bright red sandstones	22	"	"
Coarse purplish sandstones	12	"	"
Bright red clay with greenish nodules and purplish bands	100	"	"
Coarse, hard purplish sandstone	8	"	"
Bright red clay and sandstone	65	"	"
Hard red and purplish sandstone	6	"	"
Bright red sandy clay, with purplish streaks	90	"	"
Purplish and dark brown clay	22	"	"
Red clay and hard red sandstone	30	"	"
Hard purplish sandstones	35	"	"
Red clay	7	?	
Purple sandstones	3	?	
Red clay	22	?	
Permo-Carboniferous: red, brown sandstones and clays, fossiliferous			

also the other section given in this paper, will not apply in detail to any other place, since it has been our experience in the Red Beds that detailed sections made in any given place cannot be depended upon perhaps a quarter of a mile away. The top of this section, as already stated, yields vertebrate fossils of Upper Triassic age, and some of the Triassic vertebrates described by Cope from New Mexico came from the El Cobre Cañon.

A survey of the surrounding country from the summit here, as also from the Piedra Lumbre, shows everywhere these basal Upper Trias rocks as the lower or lowermost exposures.

From the El Cobre Cañon the expedition turned westward on the Chama to the mouth of Cañones creek, and then southwest across the Piedra Lumbre Mesa to El Rito, or "branch" of the Puerco. The top of this mesa is of Upper Triassic age, and, near the base of Mt. Pedernal, which rises several hundred feet above the mesa, appears for the first time the heavy layer of gypsum marking the upper limits of the Red Beds, or so-called Trias. From the top of this mesa a good view of the adjacent country is afforded. To the north is the Mesa de los Viejos, with the Chama apparently occupying a fault line between, and the Arroya Seco in a valley formed by the basal Upper Trias rocks sloping from the brim of the Cobre Cañon on the east and the superincumbent Triassic rocks on the west. To the west lie the Mesa Prieta and the smaller Capulin Mesa, separated by the Puerco, Chama, and Capulin streams, whose courses seem to have been influenced strongly by the faulting and dipping of the Trias.

The Puerco to the mouth of the Poleo has cut down into Permian strata, which attain their greatest exposure on the Poleo about one mile from its mouth. Our first camp was made on the Poleo (Arroya de Agua), about one mile above its confluence with the Puerco.[1] Near the junction of the two creeks there is a steep walled cliff of Permian rocks about a hundred feet in height, with a more or less flat table-land above it a mile or so in extent separating it from the Trias above. Farther west, where the Permian rocks find their greatest exposure, and where the Baldwin quarry is, from which so many of the fossils in the Yale collection came, the very steep bluffs, in many places so steep as to be unclimbable, are about seven hundred feet in height, composed of alternating red sandstones and clays, with white and purple sandstones, clays, and conglomerates at the upper part, corresponding quite to the massive sandstones forming the brim of the Cobre Cañon, and which form the top of the Mesa Poleo, dipping northward to the foot of the Mesa Prieta. Phytosaur bones were found at the base of this white sandstone and in the pebbly conglomerates immediately underlying them. Permian fossils were found only in the lower-

[1] This Puerco creek is not the one which gave origin to the name of the Puerco formation, a stream by the same name farther to the southwest.

most three hundred feet of these exposures, the intervening three hundred feet of more or less vertical red clays and sandstones here, as everywhere else in the Rocky Mountain region, being quite barren. These rocks lie here, as elsewhere, apparently quite conformable with the superincumbent and subjacent beds, and doubtless represent the Lower Trias and perhaps more or less of the Upper Permian. The section of the bluff herewith given was made opposite our first camp on the Poleo, about one mile from the mouth of the creek; as is the case with the section at El Cobre, it can be depended upon only for a short distance on either side; the strata often change abruptly from sandstones to clays and vice versa.

On the north side of the immediate valley of the Poleo the strata dip northward to the walls of the Mesa Prieta; immediately south of the creek they dip abruptly southward. About two miles above the mouth of the creek the beds bend down sharply and disappear beneath the alluvial deposits of the creek bed, doubtless indicating the line of a fault. Beyond this point the walls of the Mesa Prieta, formed exclusively of Upper Triassic and superincumbent beds, descend to the immediate valley of the Poleo and Capulin creeks.

The Mesa Prieta rises about fifteen hundred feet above the beds of the Poleo and Capulin. Near the middle of the bluffs, at about the 8,000-foot line, there is a heavy bed of gypsum, which is taken to be the upper limits of the Trias, though, as we have said, in the entire absence of all fossil remains through four hundred feet of these beds at least, everywhere, their age is assumed simply from their color—evidence, to say the least, that is exceedingly dubious, the more so from the fact that there is no petrological distinction between the Trias and Permian. Above this gypsum layer are the brownish and purplish shales of the Jurassic[1] and the lighter colored sandstones of the Cretaceous all lying quite conformably with the Red Beds below.

About a mile and a half beyond the little settlement called

[1] The beds immediately overlying the gypsum have been called Dakota by Darton (*Bull. U.S.G.S. No. 435*) and Shaler (*Bull. U.S.G.S. No. 315*, p. 262), but without any evidence therefor. We searched in these shales for fossils, but without success. Elsewhere the beds overlying the Trias are either the marine Sundance (Wyoming), the Hallopus beds (Cañon City, Colo.), Morrison (Southern Wyoming), or Lower Cretaceous (Kansas).

SECTION II

POLEO CREEK

Gray sandstones, mostly even grained with pebbly conglomerates and shales below. Phytosaurs	30	Upper Trias	
Softer gray sandstones, weathering into sand	30	?	
Sandy clay, with beds of thin black shale; plant remains, fossil wood	40	Upper Trias?	
Sandy clay, black and green	12	Lower Trias?	Barren
Purplish sandy clay	6	"	"
Coarse yellow sandstone	33	"	"
Loose gray sand	6	"	"
Green and purplish sandstones	3	"	"
Gray and purplish sandstones	12	"	"
Hard clay, variegated and jointed (cliffs)	3	"	"
Purplish sandstones and red clay	30	"	"
Loose white sand with beds of red clay	40	"	"
First red nodular layer	6	"	"
Soft fine-grained, light red sandstones, cross-bedded, forming tops of pyramids and cliffs	6	"	"
Soft fine-grained, light red sandstones, cross-bedded with lighter bands of pebbles	3	"	"
Second red nodular layer, with clay	3	"	"
Red clay	2	"	"
Coarse cross-bedded sandstones	6	"	"
Third red nodular layer	6	"	"
Red cross-bedded sandstones	12	"	"
Dark red and green clay	3	"	"
Coarse red and green sandstones	17	"	"
Hard red sandstones, cliffs	3	"	"
Red sandstone and clay with thin band of harder sandstone	18	"	"
Hard, red coarse sandstone	3	"	"
Red clay	35	"	"
Red sandstone, bluffs	23	Base (?) of Trias	
Red sandstone with thin seams of clay, reptile bones	18	Top (?) of Permian	
Red clay with thin nodular layers	55		
Dark red, coarse sandstones (cliffs)	6	Permian, fossiliferous	
Red sandy clay	35	"	
Dark red, coarse sandstone, jointed	18	"	
Red clay, even texture, vertical rain erosion	50	"	
Dark red clay	8	"	
Red shaly clay	17	"	
Heavy gray sandstones	25	"	
Red sandstones and clays	?	"	

Capulin a stream flows into Capulin creek from the north along the line of a fault which divides the Mesa Prieta from the Capulin Mesa. The strata of the Mesa Prieta at this point dip slightly northwest, but those of the Capulin Mesa dip east and northeast. The west face of the Capulin Mesa rises a thousand feet or thereabout above the valley of the Gallina River. Just north of the Cerro Blanco there is a high red wall similar to that north of the Poleo creek, the uppermost rocks bearing phytosaur remains. It is confidently believed that the lowermost exposures here are of Permian age, but no fossils were found.

There is a sharp break between the Capulin Mesa and the Cerro Blanco. The rocks of the latter dip sharply to the west, and are overlain by the Jurassic shales and the Cretaceous sandstones and shales. At the foot of these Upper Triassic rocks, north of Cerro Blanco, and opposite the face of the Capulin Mesa bluff before referred to were found various small fresh-water invertebrates, and bone fragments referred provisionally to the genus *Coelophysis* Cope. The horizon of these remains can hardly be less than one hundred feet above the basal Upper Trias sandstones, and, in all probability, the original types came from the immediate locality whence the fragments were found by the junior author. The Cerro Blanco takes its name from the massive beds of white gypsum which cap it, descending steeply below the creek bed to the south and dipping to the west. From the top of the Cerro Blanco one can look miles to the north and west, and the view therefrom is a revelation to the geologist. To the east lie the mesas of more or less horizontal rocks of predominantly Upper Triassic age; to the west the strata are deeply tilted and eroded into valleys; a few miles farther west the beds of the Wasatch badlands lie horizontally upon the uptilted edges of the Mesozoic strata.

Upon the whole, the general features of the Red Beds in northern New Mexico, as in many places elsewhere, may be summarized as follows:

The Upper Trias rocks, about six hundred feet in thickness, perhaps more, are predominantly softer and lighter colored, often orange colored, yellowish and whitish, and more aeolian in character, with the upper or uppermost beds more or less gypsiferous.

These beds, as in the Lander region, have basal sandstones, reddish or white, with conglomerate and clay layers below them yielding phytosaur and labyrinthodont bones (both types were found at El Rito), corresponding well with like vertebrates from the Keuper of Europe. Below these beds there are not less than three hundred and fifty feet, in the Lander and Kansas regions perhaps nine hundred feet, of more uniform red sandstones and clay layers, usually weathering into more vertical bluffs, that are utterly barren of all fossils and supposed to be of Lower Triassic and Upper Permian age. Below these and conformable with them, in New Mexico and probably elsewhere, are not less than three hundred feet, probably more, of prevailing coarser and darker colored, often brownish sandstones, and dark-colored clay beds, yielding vertebrate remains hitherto considered to be of Permian age, but which in all probability are in part at least of upper Pennsylvanian age.

ON THE DISTRIBUTION OF LOWER TRIASSIC FAUNAS[1]

JAMES PERRIN SMITH
Leland Stanford Jr. University, California

No formation has added more in recent years to our knowledge of ancient faunal geography than the Lower Triassic. In this epoch we now know three distinct and widely distributed interregional faunal zones, which are truly bench-marks in correlation. These are in sequence upward: (1) the *Meekoceras* zone; (2) the *Tirolites* zone; (3) the *Columbites* zone. They do not have the same distribution, nor are the relationships of the various regions constant for the successive epochs, showing that there was considerable change in physical geography during the Lower Triassic. Critical studies of these faunas from Siberia, India, Madagascar, the Indian Archipelago, and western America have made it possible for us to understand the ancient faunal geography in a way that was impossible a few years ago.

FAUNAS OF THE MEEKOCERAS ZONE

The Meekoceras fauna of Madagascar.—During the past year Dr. H. Douvillé[2] has announced the discovery of the *Meekoceras* fauna on Madagascar; with *Meekoceras* cf. *gracilitatis*, *Flemingites*, *Cordillerites*, and *Lecanites*, all closely allied to species in the American fauna. This argues for a connection during this epoch between the Great Basin Sea and the Indian Ocean. Madagascar and the Great Basin of western America are almost exactly opposite each other on the globe, and the distance would be about twelve thousand miles by a great circle. From the Great Basin to Madagascar around the old shore line of the North Pacific, and then down the Asiatic coast and around the old shore line of the ancient Australasian land-mass, would be about twenty-one thousand miles. But if

[1] Published by permission of the Director of the U.S. Geological Survey.

[2] *Compt. rendus. Acad. Sci.*, 1910, p. 210; and *Bull. Soc. géol. France*, 4e sér., Tome X, pp. 125.

there was an arm of the sea connecting the Indian Tethys with the southern Indian Ocean the distance would not be more than fourteen thousand miles. This geosyncline, or arm of the sea, did exist in Jurassic time, and it is probable that the occurrence of the Pacific-Asiatic fauna of the *Meekoceras* zone in Madagascar marks the birth of the Indian Ocean.

The Meekoceras fauna of the Indian Archipelago.—Dr. J. Wanner[1] has recently described the *Meekoceras* fauna of the Island of Timor in the Indian Archipelago, listing from there; *Meekoceras, Flemingites*, and *Pseudosageceras multilobatum*, with species all closely related to forms already known in India and in the Great Basin Sea, showing the existence of the Tethys during this epoch.

The Meekoceras fauna in India and Siberia.—The *Meekoceras* fauna of India has long been known, but a recent work by Diener and von Krafft[2] has added greatly to our knowledge, and has made possible exact comparisons and correlations of faunas. In this monograph Diener and von Krafft bring out very clearly the intimate relations existing between the Indian, the Siberian, and the western American faunas of this zone.

The Arctic Meekoceras faunas.—The *Posidonomya* beds of Spitzbergen have long passed as Middle Triassic, but they contain several species almost identical with forms in the *Meekoceras* beds of Idaho. They were described as "*Ceratites*" but there can be no doubt that "*Ceratites*" *costatus* belongs to *Flemingites*, and that "*Ceratites*" *polaris* and *C. whitei* belong to *Meekoceras*, very closely allied to *M. mushbachanum*, all typical of the Lower Triassic. This fauna must then be placed in the Brahmannic stage of the Lower Triassic. The only argument against this conclusion is the supposed occurrence in the Spitzbergen beds of a *Monophyllites* of Middle Triassic character. But this species is almost identical with *M. sphaerophyllus*, a group typical of the higher Muschelkalk beds of Bosnia, India, and Nevada, and the specimen probably came out of the *Daonella* beds of Spitzbergen, which do contain an upper Muschelkalk fauna. Such a

[1] *Centralblatt für Min. Geol. und Pal.* 1909, pp. 137–47; 1910, p. 736; *Neues Jahrb. für Min.* etc., 1911, Beilage Bd. No. XXXII, pp. 177–96.

[2] "Lower Triassic Cephalopoda from Spiti, Malla Johar, and Byans," *Pal. Indica.*, Ser. XV, Vol. VI, No. 1, 1909.

confusion of species might easily happen, under the conditions of collecting in that region.

The *Meekoceras* fauna of southwestern Siberia, Thibet, and India is too well known to need further discussion here. It contains this same assemblage of genera already mentioned, mostly near allies of the genus *Meekoceras*. This fauna has been described in numerous monographs by Waagen, Diener, Noetling, and Griesbach, and has become the standard of comparison for the rest of the world.

The Meekoceras fauna in western America.—In southeastern Idaho and in the Inyo Mountains of California the *Meekoceras* fauna has been described in the works of C. A. White, Alpheus Hyatt, and the writer, with a wealth of genera similar to those of Asia, and some few identical species. The most characteristic genera are: *Meekoceras*, *Aspidites*, *Flemingites*, *Hedenstroemia*, *Pseudosageceras*, *Cordillerites*, *Lanceolites*, *Xenodiscus*, *Nannites*, *Inyoites*, *Owenites*, and *Lecanites*.

The writer has recently found this same fauna near the ranch of Henry Phelan, in White Pine County in eastern Nevada, about seventy miles south of Wells station on the Central Pacific Railroad. This locality is about half-way between the localities in California and Idaho, and distant over three hundred miles from each. The following is a preliminary list of the species identified: *Meekoceras gracilitatis*, *M.* cf. *mushbachanum*, *M.* cf. *radiosum* Waagen, *Proptychites* cf. *Walcotti*, *Lanceolites* sp. nov., *Pseudosageceras intermontanum*, *Aspenites acutus*, *Inyoites oweni*, *Owenites* cf. *koeneni*, *Nannites dieneri*, *Paranannites* cf. *aspenensis*, *Ophiceras* sp. nov., *Xenodiscus* cf. *whiteanus* Waagen, *X.* cf. *nivalis* Diener, *Pseudomonotis* cf. *idahoensis*.

By a comparison with lists from Idaho and from California it will be seen that the affinities with the latter are closer than with Idaho, although the two provinces were intimately related, and the new locality in Nevada gives a perfect connecting link, as it should, from its geographic position.

The *Meekoceras* fauna is one of the most distinctive and widely defined interregional correlation zones in the world, being known from Spitzbergen on the north, through the equatorial region of

Timor, to Madagascar on the south; from India on the west, through the Tethys to southeastern Siberia, to the Great Basin Sea of western America. It is not known in the Mediterranean region, nor in South America, Africa, nor Australia. Its genera and species are closely related in all the regions mentioned, so that an intimate connection between those regions is certain. It would seem probable that at this time there was a barrier between the Poseidon Ocean and the Pacific, and between the Mediterranean and the Oriental Tethys. It is certain that there was a connection between the North Pacific and the Arctic Ocean, and that the Great Basin Sea opened into the North Pacific. It is equally certain that the North Pacific was connected with the Oriental Tethys through the Archipelago north of Australia, this narrow sea extending westward to India, and southward in a great geosyncline to Madagascar.

The distribution of the *Meekoceras* fauna rivals, and even surpasses, that of the *Arietites* fauna of the Lias. Truly, this speaks for remarkably uniform conditions in the sea of that time, but whether warm, temperate, or cold we cannot say, for we know nothing of the corals in the sea, nor of the land plants, which might give us some indication of the temperature.

THE TIROLITES FAUNA

The *Tirolites* fauna has long been known in the Mediterranean region, where it was formerly supposed to be the only one. It is especially characterized by the abundance of the genus *Tirolites*, which until recently was supposed to be confined to this region.

In recent years the writer[1] has described the occurrence of the *Tirolites* fauna in southeastern Idaho, with *Tirolites* cf. *cassianus* Quenstedt, *T.* cf. *haueri* Mojsisovics, *T.* cf. *smiriagini* Mojsisovics, *Dalmatites* cf. *morlaccus* Kittl, *Dinarites* sp. nov., etc.

This fauna is of decidedly Mediterranean character, and unlike anything known elsewhere, though Diener and von Krafft have described a single species of *Tirolites* from the Lower Triassic of India. The close relationship of the *Tirolites* fauna of Idaho with

[1] Festschrift—Adolf von Koenen (1907), *The Stratigraphy of the Western American Trias*, 398–99.

that of the Alpine Province of the Mediterranean region shows an intimate connection, not through the Oriental Tethys, but rather through the Poseidon Ocean. At that time there was no barrier between the Caribbean Sea and the Pacific, but the portal between the Pacific and the Oriental Tethys was probably closed, as was also the portal between the Oriental Tethys and the Mediterranean.

THE COLUMBITES FAUNA

The *Columbites* fauna of Idaho was described by Alpheus Hyatt and the writer,[1] from a single locality near the town of Paris. It is characterized by the abundance of the genus *Columbites*, a member of the family *Tropitidae*, *Ophiceras*, *Xenodiscus*, *Pseudosageceras*, with a few species that have survived from the older *Meekoceras* fauna. There was also found in it a single species of *Tirolites* near *T. seminudus* Mojsisovics, a survivor from the underlying *Tirolites* zone. At the time when this fauna was described it was supposed to be unique, nothing like it being known anywhere, though the writer recognized its kinship to the Olenek fauna of northern Siberia.

The section at Paris Canyon is very instructive, for there is exposed the entire sequence of the Lower Triassic. At the base are the *Meekoceras* beds—yellowish-gray limestones—about twenty-five feet thick, with *Meekoceras gracilitatis*, *Flemingites cirratus*, *Ussuria waageni*, *Nannites dieneri*, *Pseudosageceras intermontanum*, *Lanceolites compactus*, and many other forms characteristic of this horizon.

About two hundred and fifty feet higher up in the section are the *Tirolites* beds—gray calcareous shales—with the forms listed under the *Tirolites* fauna. About twenty-five feet higher is a thin bed of brownish bituminous limestone, in which the *Columbites* fauna was found, containing *Columbites parisianus*, several other species of the same genus, *Xenaspis*, *Xenodiscus*, *Celtites*, *Pseudharpoceras*, *Ophiceras*, *Meekoceras*, and *Pseudosageceras intermontanum*, besides a *Tirolites* near *T. seminudus* Mojsisovics. The *Meekoceras* and *Pseudosageceras* are survivors from the *Meekoceras* beds, while the *Tirolites* has lived over from the preceding *Tirolites* fauna.

This *Columbites* fauna in Idaho is very important in settling the

[1] *Professional Papers U.S. Geol. Survey No. 50*, 1905.

age of certain disputed beds thousands of miles away, occurring, as it does, associated with survivors from the underlying beds in the same section, and above both the *Tirolites* and the *Meekoceras* faunas in the same canyon. In the first place, this proves the Lower Triassic age of the *Meekoceras* beds, if further proof were needed, since several abundant and characteristic species range through the entire section, and since the *Tirolites* beds, only a few feet below, contain a fauna virtually identical with that of the classic Campil beds, the type of the marine Lower Triassic of the Mediterranean region. But the *Columbites* beds belong to a horizon higher than any yet found to be fossiliferous in the original Mediterranean section, that is, to the barren upper Campil beds, as will be shown later in the discussion of the Albanian occurrence of this formation.

The Olenek beds of northern Siberia have long passed as the equivalents of the upper part of the Lower Triassic, but without any definite proof. Now since the faunas of the Olenek beds of Siberia and of the *Columbites* beds of Idaho are so closely related, and the stratigraphic position of the latter is positively known, the long-desired proof is brought. The Olenek beds are Lower Triassic, but younger than the *Tirolites* beds of the Mediterranean region.

Further proof of the validity of these conclusions has recently been published by Dr. G. von Arthaber,[1] from Albania on the Balkan Peninsula. Dr. von Arthaber describes from that region an assemblage of genera very like that of the *Columbites* fauna of Idaho, with some species that he considers identical; they include: *Columbites*, *Meekoceras*, *Celtites*, *Hedenstroemia*, *Sageceras*, *Pseudosageceras*, *Nannites*, *Lecanites*, *Pronorites*, *Tirolites*, *Parapopanoceras*, etc. According to Dr. von Arthaber, *Pseudosageceras multilobatum* Noetling is the same as *P. intermontanum* H. and S., and *Nannites heberti* is identical with *N. dieneri* H. and S., and those two species are also known in the *Hedenstroemia* beds of India. I do not agree with him as to the Albanian species of *Pseudosageceras*, which seems to me to be identical with *P. intermonta-*

[1] "Ueber die Entdeckung von Untertrias in Albanien und ihre faunistische Bewertung," *Mittheil. Geol. Gesell. Wien*, I (1908), 245–89; and "Ueber neue Funde in der Untertrias von Albanien," *ibid.*, II, 1909, 227–34.

num, but not with *P. multilobatum*. In fact, it does not seem to me that any species of the Albanian fauna is identical with any from India, but that the relationship is nearer to the boreal Olenek fauna and to the American *Columbites* fauna. This seems to the writer to be a boreal fauna that came down to the Mediterranean on one side, and to Idaho on the other. We know such a boreal invasion, in the Upper Triassic, when the *Pseudomonotis subcircularis* fauna came down to the Crimea on the one side, and to California on the other. It is probable that in Triassic time there was a depression connecting the Mediterranean with the Arctic Sea, and that periodic migrations came southward through this. In Idaho it was undoubtedly such an incursion. It is possible, however, that the appearance of the *Columbites* fauna in Mediterranean waters may be the beginning of an Indian immigration, which culminated in the lower part of the Middle Triassic as recorded by the Indian fauna of the Gulf of Ismid in Asia Minor.

To sum up, it seems probable that during the Brahmannic epoch of the Lower Triassic the Indian Region was the distributing point for the *Meekoceras* fauna, and that the swarming inhabitants of that sea migrated outward in all directions where marine connections permitted, reaching Spitzbergen on the north, Madagascar on the south, and the Great Basin Sea on the east; but that there was no connection between the Oriental and the Mediterranean divisions of the Tethys, nor between the Mediterranean-Poseidon waters and the Pacific.

During the *Tirolites* epoch a connection was opened between the Mediterranean-Poseidon Ocean and the Great Basin, but the latter body of water was not connected closely with the Arctic Ocean.

During the *Columbites* epoch the center of distribution of the known faunas seems to have been the Boreal Sea, from which migrations came southward to the border of the Mediterranean region, probably through Asia, and down to the Great Basin through the northern passage. There was probably no direct connection between the Poseidon-Mediterranean Ocean and the Pacific, nor any very close union between the eastern and the western divisions of the Tethys.

These periodic shiftings of ancient geographic relations do not show shiftings of the ancient seas, but rather prove the periodic opening and closing of the gateways connecting them. These gateways, or portals, are areas of depression on or between continental masses, and lie in regions of permanent instability of the earth's crust, where mountain-building, and the accompanying volcanic and earthquake disturbances have been prevalent. Some of these ancient portals are temporarily open now, on account of recent subsidence, as, for instance, the Bering Strait; another has been recently opened, by the activity of man—the Suez Canal. And the Panama Canal will restore a connection between the Atlantic and Pacific, which is temporarily closed on account of recent elevation in that region. One of these portals, that connecting the Oriental Tethys with the southern waters, has expanded into the Indian Ocean. Others of the ancient portals are now concealed in continental masses, and their very existence would not be suspected without studies in interregional relationships of faunas.

PANTYLUS CORDATUS COPE

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The University of Chicago

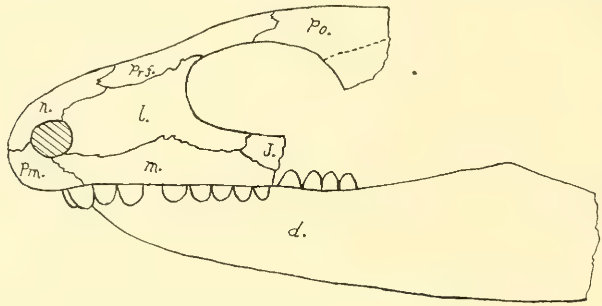
E. C. Case, in his recently published revision of the Cotylosauria of North America, has given to the genus *Pantylus* Cope the rank of a suborder, the Pantylosauria. Nothing is known of the genus aside from the skull and even that is more or less incomplete in the two hitherto known specimens. *Pantylus* is peculiar in so many respects that any new facts concerning it are of interest. It is for this reason that the writer here describes another specimen which, though incomplete, adds some additional facts of importance especially as regards the dentition.

The specimen herein described was collected by Mr. P. C. Miller, of the University of Chicago expedition of 1908, from the Lower or Wichita division of the Red Beds of Baylor County, Texas, near the Big Wichita River. It consists of the anterior part of the cranium, as in the type, the anterior part of the left mandibular ramus, and a nearly complete right ramus. Unfortunately the posterior part of the skull is missing, but it is fairly complete from a point a short distance back of the posterior border of the orbits to the muzzle. A little of the posterior end of the right ramus is missing, but nearly the entire length is represented and the dentition is complete.

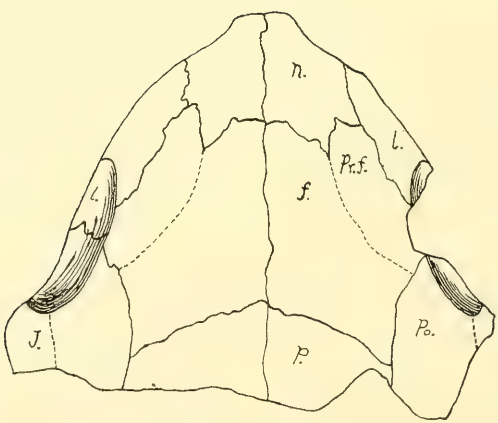
As shown in the appended table of comparison, the specimen is somewhat larger than the type. Although the posterior part of the skull is missing, its width must have been greater than the type, for the spread of the mandibular rami is at least 92 mm. Fig. 1*b* shows the anterior part of the cranium with most of the sutures indicated. Those between the premaxillaries, maxillaries, lachrymals, nasals, and parietals are distinct.

There is no trace of the sutures between the postfrontals and the prefrontals. In fact, there are but slight traces of the suture between the frontals and prefrontals, and this suture, with that

between the jugal and postorbital, is for this reason indicated by dotted lines. A comparison with Cope's figure[1] will bring out a few differences. The maxillary bone is here shown as taking part



1a



1b

FIG. 1.—*Pantylus cordatus* Cope. 1*a*, side view of skull with jaw attached. 1*b*, top of skull showing sutures. Figures natural size.

in the orbit. As indicated in Fig. 1*a*, the maxillary enters slightly into the external nares, but is excluded from the orbit by the lachrymal and jugal which unite in the inferior border of the orbit about

[1] *Trans. Am. Phil. Soc.*, XVII (1892) 25, Pl. 1, Fig. 4.

midway. This is essentially as Case has figured it.[1] The lachrymal extends back from the nares in a broad triangle and forms the entire anterior border of the orbit. It forms the floor of the front half of the eye cavity and extends inward nearly to the nares.

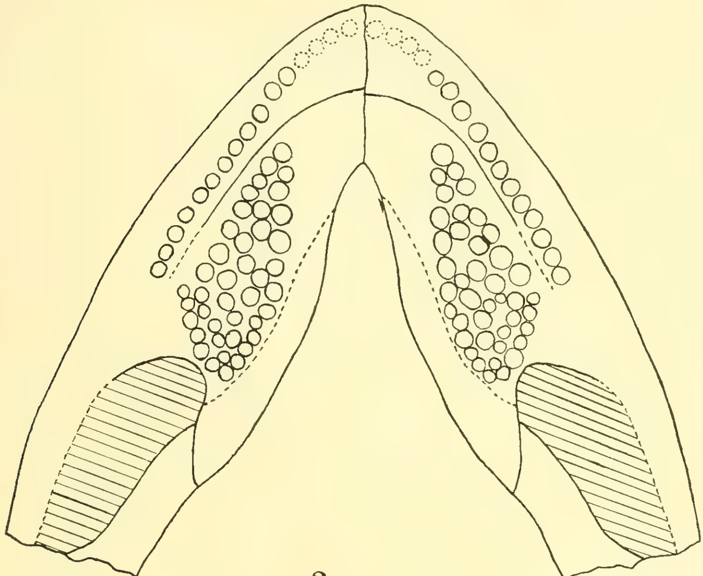
The arrangement of the palate bones, so far as one can make it out, is much the same as that in *Captorhinus*. The premaxillary is probably short and does not enter very largely into the internal nares. The prevomers are rather broad and well developed. They lie along the inner side of, and extend nearly to the posterior border of, the nares. The pterygoids, of which the posterior end is missing on both sides, send forward rather broad processes that converge in a gentle curve and meet at a point a little back of the posterior border of the orbits. From this point they extend forward, gradually narrowing and separating the prevomers fully half their length. In cross-section the pterygoids are angular, one side lying in the plane of the palate, the other extending vertically nearly to the cranial roof. Back of the nares and forming their posterior border lie the broad, platelike palatines. They extend inward toward the median line, underlying the pterygoids and extending upward along the inner angle of these bones. The transverse bones, if present, are indistinguishable.

Dentition.—While the upper dentition is probably not complete in this specimen, the essential features are readily made out. The premaxillary bears two teeth, the first of which is the larger, 4 mm. or more in diameter. The maxillary bears eight teeth and probably about four more of the posterior ones are broken away. The first two of these exceed those following in diameter and height, the second being the larger of the two and measuring but little less than the first premaxillary tooth. The remaining maxillary teeth are slightly oval in cross-section rather than circular and are sub-equal in diameter and height, these measurements being about 2 mm. and 2.5 mm. respectively. The prevomer region of the palate was exposed from above as the matrix below was very hard and was protected by the anterior part of the mandible. Hence it cannot be said with certainty whether the prevomers bear teeth or not, but in all probability they do. On each palatine there is a large,

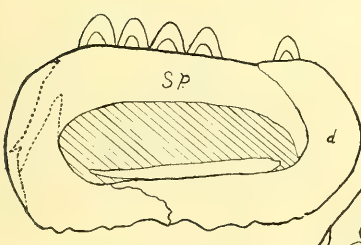
[1] *Publication No. 145*, Carnegie Institution of Washington, p. 114, Fig. 52*c*.

rather well-defined pad of teeth, which in shape and size corresponds to a similar pad on the splenial. Measurements show that these two pads are exactly opposed posteriorly. Anteriorly, however, the lower pad apparently underlies the posterior part of the narial opening. The teeth of the palate group vary considerably in size and basal cross-section, apparently with no definite arrangement as to height or diameter. Most of the larger teeth, however, are disposed anteriorly although some of the smallest crowd closely on the posterior border of the nares. These palatine teeth are the same shortly conic, obtuse form as those of the lower dentition. They vary from 1.5 mm. to 3 mm. in height and from 1 mm. to 4 mm. in diameter. On the palatines one is able to make out about twenty teeth. The pterygoids are studded with irregularly placed, small, conical teeth, some fourteen of which are shown in the figure. These vary somewhat in size, though all are small, some being little more than mere points. Apparently all are hollow as are the other teeth.

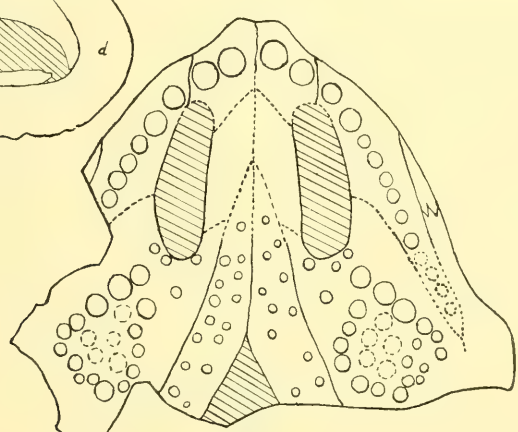
Mandible.—The nature of the lower jaw is given by E. C. Case in his revision of the Cotylosauria (p. 114). Fig. *2b* shows a cross-section of the right ramus at the third tooth from the last in the dentary series. The suture above separating the dentary and the splenial is readily made out, as is that intersecting the broad lower surface of the ramus. It is the upper, inner element of the mandible that bears the pad of teeth referred to above. Clearly this is the splenial. Besides these sutures which are easily seen, it is possible that two other elements are shown as indicated by the dotted lines; one with an angular cross-section on the lower, inferior angle of the ramus, and a thin platelike one on the inferior surface. Immediately above the dentary, within the central cavity, lies a thin plate of bone that is apparently no part of the dentary or the element joining it. The central cavity is confluent with the large orifice immediately posterior to the splenial group of teeth, as shown in Fig. *2a*. From the dentary foramen a well-marked suture runs up and forward to the inner, anterior margin of the Meckelian orifice. Further than this, one is unable to make out the sutures with any degree of certainty. Like the other dimensions of the specimen, those of the lower jaw are greater than in the type specimen as shown in the table.



2a



2b



2c

FIG 2.—*Pantylus cordatus* Cope. *2a*, lower jaw showing dentition. Natural size. *2b*, cross-section of right ramus at the third tooth from the last in the dentary series. Figure twice natural size. *2c*, palate view showing dentition. Natural size.

The greatest interest of the specimen probably lies in its mandibular dentition. Beyond a doubt the larger number of teeth are on the splenial bone instead of the dentary. Unfortunately the crowns of most of the teeth of the mandible were destroyed in the separation of the rami of the skull. One is able nevertheless to make out the arrangement of all the teeth except for a short distance on the anterior border. This space is well beyond the termination of a regular, definitely outlined inner pad of teeth, however, and most likely only the outer row is continued forward. Judging from the size of the teeth exposed in the outer row, there are four teeth hidden in this anterior part of each ramus by the matrix of the projecting muzzle. As suggested above, the teeth are arranged in two groups, an outer row of sixteen teeth, the posterior twelve of which are shown, and an inner pad or series. In the outer row they apparently do not vary greatly in cross-section. As to any variation in height of crown I am unable to say. This series, I am confident, comprises the only teeth on the dentary. The inner series is arranged in a pattern of regular shape. The outline of this pattern is formed by a band of twenty-five teeth which become progressively smaller posteriorly from nearly 3 mm. in cross-section at the anterior border to 1.5 mm. at the posterior side. Within this peripheral band are fifteen irregularly disposed teeth. In cross-section these range from 4 mm. to 2 mm., the larger being disposed anteriorly. It is impossible to determine the height of the crowns of this inner series but it is certain that some of them were higher than the regularly placed peripheral group. It is interesting to note that while the teeth of the inner series show a circular section midway between the base and the apex, the base often shows a polygonal cross-section and here only small interspaces are left between the teeth.

In Cope's description of *P. coicodus*, the second species of this genus, the chief distinguishing features are found in the teeth. They have a pointed apex like the grass seed *Coix lachroma*, while those of *P. cordatus* are obtuse. *P. coicodus* also has "partially pleurodont" teeth with a swollen crown on a shanklike base. Case suggests that the obtuse tooth of *P. cordatus* is simply that of *P. coicodus* with the pointed apex worn down and that the two species

are not distinct. In the specimen here described the teeth do not appear to be greatly worn and they probably never had the pointed apex. The shanklike base is also wanting and the teeth are distinctly acrodont. For these reasons I believe that *P. coicodus* and *P. cordatus* are distinct species. And, furthermore, if Cope was correct in his statement that *P. coicodus* has a partially pleurodont dentition, the differences seem to be greater than specific.

The dentition would suggest peculiar food habits for the animal. The lack of sharp teeth certainly indicates that its food did not require cutting. In all probability the dental armature was an adaptation for the crushing of shells of gastropods and other molluscs.

A COMPARISON OF MEASUREMENTS

	Type Specimen	Described Specimen
Length of axis of cranium to line connecting anterior border of orbits	0.018 m.	0.020 m.
Inter-orbital width	0.032	0.040
Longitudinal diameter of orbits	0.016	0.021
Length from orbit to nostril	0.015	0.018
Height of crown of large maxillary tooth	0.0045	0.003
Width of mandibular ramus below at middle	0.020	0.027
Length of part of ramus preserved	.....	0.084
Spread of rami at greatest length	.....	0.092
Width of cranium at line connecting posterior border of quadrates	0.077	.....

NOTES ON TERTIARY DEPOSITS NEAR COALINGA OIL FIELD AND THEIR STRATIGRAPHIC RELATIONS WITH THE UPPER CRETACEOUS

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The work of the California division of the geological department of the Southern Pacific Company during the spring of 1910 was devoted in part to the differentiation and careful definition of the oil-bearing formations of the Coalinga district and the area lying north of it and the mapping of the surface exposures of each as accurately as conditions would permit. Two field parties were engaged in this work, one of them comprising Mr. J. A. Taff, assisted by Mr. B. L. Cunningham, and the other Mr. F. M. Anderson, assisted by Messrs. G. C. Gester and E. A. Hardy. The work begun here is being extended to cover the west side of the San Joaquin Valley. As soon as the collections and field data have been properly studied, it is hoped that papers may be published by these geologists giving the geological details fully, but, since such publications may be delayed, I have arranged the following statement of some of the results of the early work, based on their preliminary reports and maps.

PREVIOUS WORK

The first two publications based directly upon the work of this department in this area were those by Mr. Frank M. Anderson, entitled "A Stratigraphic Study in the Mount Diablo Range of California,"[1] in 1905, and "A Further Stratigraphic Study in the Mount Diablo Range of California,"[2] in 1908. Prior to our work, we have only the reports of Mr. W. L. Watts in *Bulletins Nos. 3* and *19* of the California State Mining Bureau and the paper of Mr. George H. Eldridge in *Bulletin No. 213* of the United States

[1] *Proc. California Acad. Sci.*, 3d series, Geology, II (1905), 156–248.

[2] *Ibid.*, 4th series, Geology, III (1908), 1–40.

Geological Survey. Later publications on the area are those of Messrs. Arnold and Anderson in *Bulletins Nos. 357, 396,* and *398* of the United States Geological Survey.

A careful study of these publications indicates that no one has been able clearly to differentiate the basal beds of the Tertiary from the upper beds of the Cretaceous, and that the parting as drawn was purely suppositional. The Tejon was the only member of the Eocene positively identified, although Mr. Anderson suggests the possible Martinez age of some lower beds.

In the Neocene, the different divisions were fairly well established and while the Monterey or lower middle Miocene fauna seemed lacking, the sediment is probably represented by a peculiar formation called the Big Blue and the equivalency of the two was suggested.

THE CRETACEOUS-TERTIARY CONTACT

Through much of this territory the uppermost Cretaceous is represented by shales and the basal Tertiary is also shaly in character. This fact has made it difficult to clearly distinguish the one from the other or to mark their parting. In the earlier publications it was supposed that there was no appreciable break in the sedimentation of the two periods, and that there was also an overlapping of faunas. This latter supposition was disproved by the work of Messrs. Stanton, Merriam, and Weaver in their studies of the region north of Mount Diablo, and we now have also conclusive proof of great stratigraphic breaks, not only between the Cretaceous and the Eocene, but also between the formation to which these basal Eocene beds belong and the overlying Tejon, which was originally supposed to represent practically the entire Eocene of the California section.

The evidence of the stratigraphic break between the Cretaceous and Eocene is somewhat more clearly shown at a point outside this territory than has yet been proven within it, and our study of this section enables us to trace the parting in the territory under discussion.

Some six or seven miles southwest of Antioch and in the eastern foothills of Mount Diablo, there is a short canyon where a slight sipe of oil was found, from which circumstance it was given the

name of Oil Canyon. A few years ago, two or three wells were sunk here in a search for oil, but failed to develop it. The north bank of this canyon gives us very distinctly the relations of the Cretaceous and Eocene.

The Chico is represented through the greater part of its exposure by a purple shale identical in appearance with that of the Coalinga region. Through a part of this shale there are beds of concretionary clayey limestone with ammonites and other Chico forms. Above this, the concretions, scattered irregularly through the shale, take the form of a very fine-grained blue limestone which weathers perfectly white. Toward the eastern end of the exposure this purple shale is overlain by a gray sandstone weathering brown. It is rather coarse grained as a whole, even conglomeratic in places, and is quite massive in structure. It carries limy concretions which contain fragments of Inocerami.

The lowest Eocene or Martinez deposit begins with a brown sand and sandy shale, more or less glauconitic, with limy concretions carrying a Martinez fauna. Higher in the section the shaly nature of the beds becomes more pronounced and they carry concretionary nodules of limestone and ironstone. Near the center of the section, as exposed here, there is a band of coarse red sandstone with some greensand, green mica, and casts of fossils. It is only a few feet in thickness and is succeeded by brown shales which carry more and more clay toward the top and more numerous and larger concretions of clay-ironstone, and lime.

At the west end of this section, opposite the head of Oil Canyon, the Martinez sandy shales rest on the Chico purple shale immediately above the band of the clayey limestone with ammonites. Going eastward a mile, higher and higher beds of the Chico shale appear under the Martinez until, at a horizon fully 125 feet stratigraphically above the first observed contact, the point of the sandstone wedge comes in and thickens until there is a body of at least 80 feet of it exposed below the Martinez.

While the exact point of contact is difficult to place where the two shale beds come together, it is entirely possible to say within a few feet of such contact, "This is Chico," or "This is Martinez," from their dissimilarity. On the sandstone, however, the contact

is sharply defined. There are numerous borings in the top of the Chico sandstone which are filled with the fine gravel and sand of the Martinez, and covering the surface is a layer of glauconitic sandy material with imprints of small shells, which is the base of the Martinez. This grades upward into the sands and sandy shales with concretions and nests of Martinez fossils.

With this section in mind, the tracing of the contact in the area north of Coalinga is not so difficult. The top of the Chico comprises purple shales and concretionary sands, and the base of the Martinez, while of much more argillaceous character than at Oil Canyon, is yet distinct.

MARTINEZ FORMATION

To Messrs. Stanton, Merriam, Weaver, and Dickerson[1] is due the credit of demonstrating in the Mount Diablo region the existence below the Tejon of a series of beds of Eocene age, which is clearly distinguishable from that terrane by its characteristic fauna and unconformable relationship. This has been named the Martinez, but only meager accounts of its stratigraphy are available and its existence was recognized at only a few localities.

Our work now proves that this lower member of the Eocene is of very considerable extent southward on the west side of San Joaquin Valley; that it consists of three or more clearly defined members, and that, in addition to the unconformity already described between it and the Cretaceous, there also exists a decided unconformity between it and the overlying Tejon.

The Martinez is well developed in Townships 17 and 18 South, Ranges 13 and 14 East, in the Salt Creek-Cantua region, and comprises a basal bed of chocolate shales with glauconitic sands overlain by yellow sands and conglomerates and these overlain in turn by other chocolate shales. The generalized section of the Martinez in this particular area may be stated as follows:

[1] T. W. Stanton, "The Faunal Relations of the Eocene and Upper Cretaceous on the Pacific Coast," *17th Rep. U.S. Geol. Survey* (1895–96), pp. 1011–60.

J. C. Merriam, "The Geologic Relations of the Martinez Group of California at the Typical Locality," *Jour. Geol.*, V (1897), 767–75.

C. E. Weaver, "Contribution to the Paleontology of the Martinez Group," *Univ. Calif. Publ. Bull. Dept. Geol.*, IV (1905), 101–23.

Roy E. Dickinson, "Stratigraphic and Faunal Relations of the Martinez Formation to the Chico and Tejon North of Mt. Diablo," *Univ. Calif. Publ. Bull. Dept. Geol.*, VI (1911), 171–77.

3. Upper chocolate shales, comprising bluish shales at top, grading down into chocolate or brown shales which weather to clays.		
These rest upon other chocolate shales which become sandier toward bottom. These shales vary in thickness	FT. 600–900	
2. Yellow sand and conglomerate.		
Bluish sandy shales and thin sandstone, variable in thickness	200	
Massive yellow sandstone with large dark brown segregations and concretions and some layers of bluish sandy shale	300	
Fine sand with local beds of conglomerate interbedded with blue and brown shales; a considerable amount of glauconitic material at base	300	
1. Lower chocolate shales.		
Beds of chocolate and brown shale with small ferruginous and limy concretions and layers of glauconitic sand. . .	1,000	
	———	2,700

Mr. Anderson reports the following forms collected from the top of the lower chocolate shales at a locality on Salt Creek in the SW $\frac{1}{4}$ of NW $\frac{1}{4}$ Section 25, Twp. 18 S., R. 14 E.:

Corbula horni Gabb
Meretrix fragilis Gabb
Leda gabbi Conrad
Margaritella angulata ? Gabb
Helicaulax costata Gabb
Ataphrus crassus ? Gabb
Neverita globosa Gabb
Arca horni Gabb
Architectonica horni Gabb
Rimella canalifera Gabb
Bulla horni Gabb
Nucula truncata Gabb
Modiola ornata Gabb
Pectunculus sp.
Discohelix californica Weaver
Turritella pachecoensis Stanton
Cucullea matthewsoni Gabb
Arca biloba Weaver
Dentalium sp.
Cylichna costata Gabb
Barbatia morsei Gabb
Spiroglyphus tejonensis Arnold
Pleurotoma fresnoensis Arnold
Corbula paralis Gabb
Venericardia alticosta Gabb
Numulites
Shark teeth

While a number of these forms are common to the Tejon and Martinez, there are several that are characteristic of the Martinez, and this, taken with the relation of these beds to the overlying Tejon, makes it necessary to refer them to the Martinez.

The greatest surface exposure of these beds in this area is found in Twp. 17 S., R. 13 E., where except for a band of Cretaceous along the south line they form the surface rocks for the entire southern half of the township. The exposure of the lower shale is only a half to three-quarters of a mile in width and the upper shale occupies a similar belt, but the yellow sandstone member has an average breadth of exposure of nearly two miles. On the eastern line of this township this is narrowed to half a mile and the three members cross the north line of Twp. 18 S., R. 14 E., with a total width of less than two miles. This is again narrowed toward the southeast until in Section 23 of this township the upper brown shale and the greater part of the yellow sand has been removed by pre-Tejon erosion, and, south of that point, so far as it occurs, the Martinez is represented beneath the Tejon only by the basal shale with a thin band of yellow sand overlying it through a part of the area.

TEJON FORMATION

The series of sediments here assigned to the Tejon admit of separation into two distinct members; the lower of white sand and conglomerate carrying a fauna in all respects identical with that of the original Tejon locality, and an upper member of white shale which is not so fossiliferous and which, as has been suggested by different investigators in this area, may in part or as a whole represent the Oligocene.

The general section of the Salt Creek-Cantua region is as follows:

5. White shale.		
White fissile organic shales, containing fish scales, teeth, foraminifera, etc.	FT. 500	
Lenses of fine brown sand.		
White shale with local thin sandy strata	1,000	
Local friable sand	0–30	
Pink to white shale	200	
Bluish sandy shales grading up into pink shales	40	
		1,770

4. White sandstone and conglomerate.		
Yellowish to white, usually fine sand	100–160	
White massive sandstone and conglomerate with whitish shale inclusions at the base	20–40	
		200

In this portion of the field the base of the Tejon is a fossiliferous conglomerate and sandstone which shows distinct unconformity with the underlying Martinez. Thus, on the east line of Section 17, Twp. 19 S., R. 15 E., the base of the conglomerate is upon an oxidized zone and the massive sandy shale immediately below the conglomerate is cut by numerous burrows that appear to have been made by crustaceans, in some cases extending down to a depth of three feet. These burrow holes have been filled with ferruginous sand and gravel conglomerates that are connected directly with the overlying conglomerate. To the northwest in Twp. 17 S., R. 13 E., where the conglomerate rests upon the upper shale of the Martinez, it contains shale inclusions at the base.

Here, as elsewhere, the Tejon carries coal locally. These coal seams occur near the base and as thin stringers higher in the section, but in this area they have not proven to be of economic value. It is interesting to note that the coal north of the Cantua occurs above the conglomerate, which we here make the base of the Tejon, while west of Coalinga it occurs below a similar conglomerate. At the Oil Canyon locality, described under the Martinez, the Tejon beds are coal bearing only in their upper portion, that is, from 250 to 300 feet below the top, while below the coal-bearing beds there is probably a thickness of 600 feet of shale before the heavy conglomerate, which there marks the base of the formation, is reached. For this reason, it would seem that either this member of the Tejon has much decreased in thickness or that only the upper portion of the beds as seen at Oil Canyon are represented there.

While the exposures of the upper white shale are excellent through Coalinga–Salt Creek–Cantua area, the few fossils obtained during this examination do not give any more definite grounds for determining its age than those before known. It apparently succeeds the lower member of the Tejon without unconformity and is highly unconformable with the succeeding Vaqueros beds of Lower Miocene age.

MIOCENE

The character and divisions of the Miocene in this region have been quite fully described in the publications referred to and especially by Messrs. Arnold and Anderson in the Bulletins of the United States Geological Survey. The divisions present in this area are as follows:

5. Etchegoin
4. Jacalitos
3. Santa Margarita
2. Monterey?
1. Vaqueros

1. VAQUEROS

The Vaqueros comprises all beds found between the Tejon and the Big Blue, the basal non-fossiliferous member of Santa Margarita of Arnold. It is predominatingly sandy, with conglomerate at base, and very fossiliferous as a whole. It lies with marked unconformity upon the Tejon. The basal unconformity which has been described and fully illustrated elsewhere is marked in Twp. 17 S., R. 14 E., by the absence of its lower beds, the upper portion resting directly on the Tejon white shale.

2. MONTEREY

The series of light-gray, fine-grained sand and clay that appear bluish when moistened, which lies between the Vaqueros and Santa Margarita, has been called the "Big Blue" and its possible Monterey age has been suggested by Arnold, who classed it tentatively with the Santa Margarita. It has a thickness of nearly 300 feet in the oil field, but appears to be somewhat thinner toward the northwest. It is clearly separated from the Vaqueros beds below and the Santa Margarita above.

In Twp. 17 S., R. 14 E., it occurs as bluish shales that in places are variegated reddish and yellow, succeeded by sandy bluish shales intermixed with gravel, having a total thickness of about 200 feet. The shales are unfossiliferous here as elsewhere, but are easily separable from the Santa Margarita, since the basal conglomerate of that formation contains a wealth of typical Santa Margarita fossils.

The stratigraphic position of the Big Blue north of Coalinga is

the representative, in part at least, of the Monterey in the Sunset-McKittrick field. At its most southern exposure in Section 29, Twp. 19 S., R. 15 E., just before it is lost under the overlapping Jacalitos, it appears as a white, apparently organic, silicious shale very similar in appearance to and in the same stratigraphic position as the shale of the Monterey where it emerges from this overlap in the southern part of the Coalinga field. That the Big Blue is the attenuated northern and more littoral representation of the Monterey is clearly evident.

SANTA MARGARITA

The base of this division of the Miocene in the Coalinga field is marked by the *Tamiosoma* zone and is overlain by sands and gravels with a total thickness of 600 feet. It is overlain unconformably by the later formations. These features continue northward but gradually the lower member grades into a remarkable conglomerate. On Salt Creek thick beds of heavy serpentine conglomerate occur in it and near the south edge of Twp. 17 S., R. 14 E., it becomes a variable deposit of coarse irregular serpentine breccia with beds of conglomerate, sands, and shale. The size of the material gradually decreases toward the northward along the outcrop and the fragments show greater wear. The beds contain the typical Santa Margarita fossils and are overlain by the sandy clays and gravel beds of its upper member.

JACALITOS AND ETCHEGOIN

The beds described under these names in the Coalinga field and supposedly separable there by the fossils contained in them continue northward, but generally without the fossils, so that it is difficult to separate the two in Twps. 18 N., R. 14 and 15 E., and 17 N., R. 13 and 14 E., and in fact to distinguish between them and the overlying Pliocene, the entire measures as exposed being a variable series of sandy clays, sands, and gravel beds aggregating 1,800 to 2,000 feet in thickness below the alluvial deposits to the east.

We were unable clearly to differentiate the Jacalitos and Etchegoin in the Coalinga region, since we found more than one Glycymeris zone in them, neither of which was mappable throughout

the field, and the Jacalitos-Etchegoin appears to be one progressive series overlapping far upon older rocks during a period of long-continued submergence.

RESULTS

Taking the results as a whole, it is probable that the most prominent and important geological fact brought to light is the continued and repeated oscillations of this part of the territory in Tertiary time, as opposed to the former idea of a practically uninterrupted sedimentation—proving that land areas existed here at the end of the Chico, the Tejon, and the Santa Margarita, and probably at the end of the Martinez and the Monterey.

The most extensive of these emergences was that between the Cretaceous and Tertiary; the next that between the Eocene and Miocene. Those between the Martinez and the Tejon and that at the end of the Monterey are not so definitely made out as yet, but there is good evidence of their existence.

The results of temporary oscillations occurring between or during these times are clearly apparent in the local unconformities existing in the various formations.

KAURI GUM MINING IN NEW ZEALAND

R. A. F. PENROSE, Jr.

Several years ago, while on a trip to New Zealand, the writer had an opportunity to see something of what is known as kauri gum mining in that country. This industry consists of digging a resinous material which in bygone times has exuded from kauri trees and has become imbedded in the soil or subsoil, where it exists in a fossil condition, often in remarkably large quantities.

The kauri tree (*Agathis australis* Salisbury; *Dammara australis* Lambert) is characteristic of certain parts of New Zealand, though it is confined geographically to narrow limits, and is most abundant from Cape North southward to the Auckland peninsula, in about latitude 37° S., a distance of about 200 miles, where its gigantic size makes it the monarch of the forests. It is found but rarely south of latitude 38° S. It occurs most plentifully at rather low altitudes, and is rare at elevations of over 1,500 feet, though some trees have been found at 2,500 feet or more.[1]

The kauri tree has a straight, symmetrical trunk, rising frequently from eighty to one hundred feet in height and sometimes even as much as one hundred and twenty-five or one hundred and fifty feet. In diameter the full-grown tree varies from four to twelve feet, while in extreme cases it may measure twenty feet or more. The top of the tree is large and spreads out in heavy branches, while the trunk is comparatively smooth, with a gray bark which peels off and collects in heaps at the base of the tree. The kauri is not so large as some of the largest of the redwood (*Sequoia*) trees of California, but it occupies the same position of prominence in the New Zealand forests as do the latter on the western coast of the United States. Like the redwoods also it is very valuable for lumber, and many of the once magnificent forests have been cut down, but enough remain to attest to their former grandeur.

[1] T. Kirk, *The Forest Flora of New Zealand*, Wellington, N.Z. (1889), p. 150.

The so-called kauri gum is really a true resin and not a gum, but the latter term has become so generally used that it is here retained. The material is a solidified turpentine which exudes from the tree as a clear, transparent liquid and hardens rapidly on exposure to the air, assuming then a dull white or slightly yellowish appearance. It collects in large quantities on all parts of the trees, on the leaves, in masses on the branches and trunk, and throughout the bark. The heaps of bark that peel off and collect on the ground are saturated with it and become solidified. These fresh exudations, however, supply very little of the gum of commerce, most of the latter being a fossil gum which has come from the secretions of the kauri trees, and has accumulated in the soil of the forests, or in the clay or other formations below the soil. It is of a light or dark brown color, sometimes almost black, transparent to translucent in luster, generally more or less homogeneous in character, but sometimes including leaves, sticks, and insects. There is a popular impression in New Zealand that the fossil gum, through some process underground, has become purer than the fresh gum from the trees.

Kauri gum occurs both in regions now covered, or which have until recently been covered, with kauri forests, and also where no kauri trees have been known to grow in historic times, but where they existed in bygone ages and have been destroyed by fire, submergence, or other causes. In fact, the larger part of the kauri gum mined in New Zealand is derived from open country, called "gumfields," destitute of any considerable timber, while the old roots and other parts of trees found under the soil prove that kauri forests once existed there. It is generally supposed that in such cases the forests were destroyed by fire, and the burned character of the remains of the trees found with the gum lends some evidence to such an hypothesis. On the other hand, it has been suggested that a fire that would destroy a forest would also destroy such an inflammable material as the gum; but it must be remembered that the gum that had become buried in the soil would be more or less protected from fire. Moreover, the gum is so abundant that though much of it might be destroyed in a burning forest, yet much might escape.

In some places gum is found in the ground underlying forests in which few or no kauri trees occur, but its origin is shown by its occasional association with the remnants of kauri trees and by inclusions of leaves. In such instances the original kauri forests have long since disappeared and the present flora represents a subsequent growth. A remarkable case of this is described by Mr. Bagnall[1] at Turua, in New Zealand, where a forest composed mostly of

FIG. 1.—Kauri gum mining in New Zealand

kahikatea trees covers an area in which kauri gum is remarkably abundant. The gum is often more or less charred by heat and is associated with the remains of kauri trees. Mr. Bagnall thinks that some of the kahikatea trees in this region are not less than one thousand years old; and though parts of this forest may have existed before the kauri forest disappeared, yet we see in this case a suggestion that possibly gum deposits may sometimes be of

[1] L. J. Bagnall, "Notes on the Occurrence of Kauri-Gum in the Kahikatea Forest at Turua," *Trans. and Proceed., New Zealand Institute*, XXIX (1896), 412–13.

considerable age. In the locality in question, the gum was so abundant that as much as half a ton is said to have been taken from twelve square feet of ground.

Kauri gum also often occurs in swamps covering buried forests of kauri trees. New Zealand is a volcanic country, and frequent movements in the earth's crust occur, so that many kauri forests which once flourished on dry ground may become partly or wholly submerged, and may die and eventually be buried in swamps. The same result may occur where a lava flow obstructs a stream, forming a lake, which inundates a kauri forest. The lake may eventually be filled up, first becoming a swamp and then perhaps dry land again, inclosing the dead trees with the earthy accumulations. In either case accumulations of kauri gum may occur with the remains of the old forests.

Considerable kauri gum is also obtained in districts from which the kauri lumber has only recently been cut, while some is mined in the soil of still standing kauri forests, and a certain amount has been obtained by tapping the trees, but the practices of mining in living forests and of tapping have been largely prohibited as injurious to the trees.

The gum usually lies from a few inches to several feet in the soil or underlying clays and sands, though sometimes it is exposed on the surface. A depth of from two to four feet is common, and a greater depth is often encountered. On the dry uplands it is usually shallower than in the swamps, where it may sometimes be twelve feet or more in depth. It occurs in irregular lumps, from a few ounces to several pounds in weight, lumps of from ten to twelve pounds being not uncommon, and in rarer cases lumps of as much as fifty or one hundred pounds have been found. It is in very variable quantities in the soil, being in some places too scattered to work profitably, in others abundant.

In some places successive layers of clay or sand carrying gum have been found, one above the other and separated by barren layers. Sometimes there are three or four of these gum layers and they represent the sites of former kauri forests which have been successively destroyed. The gum from each forest accumulated in the soil and became more or less covered with earthy matter

which served to separate it from the next layer of gum formed from the next succeeding forest. In many gum fields, which were supposed to be exhausted when the top layer was worked out, the discovery of lower layers of gum has added fresh activity to the industry.

Kauri gum mining, or "gumming" as it is often called, is generally looked on as a rather poor occupation by the New Zealanders,

FIG. 2.—Kauri gum mining in New Zealand

and is often resorted to by people out of employment, or by miners who have not been successful in locating gold, silver, or other more permanent mines, and have taken to gum mining to get the means of continuing their prospecting. In this way the industry has afforded many a poor man funds to bridge over times of distress. There is in parts of New Zealand quite a large Austrian population, and these people have often been active in the gum industry, at times making considerable profits from it. The native Maoris resort to gum mining at idle times or when their crops fail. Gum mining is a simple process, and requires but little equipment, so

that it is peculiarly fitted for those operating without capital. A long pointed iron or steel rod, or spear, is used to explore the soil, and is stuck into the ground from spot to spot, until a lump of gum is located, which is then dug out by a spade. In swampy land, where the gum is in soft mud, a hook is sometimes used to pick it out. Where gum is very abundant the whole ground is sometimes dug up without "spearing" or "hooking."

FIG. 3.—Preparing kauri gum in New Zealand

Kauri gum mining began about 1847 and has continued ever since with varying annual productions. The production in 1856 was 1,440 tons; in 1893 it was 8,317 tons;[1] in 1903 it was 9,357 tons, and in 1910 it was 8,693[2] tons. Up to the end of 1906 the total product of kauri gum in New Zealand has been estimated at 275,319 tons, valued at £13,443,017.[3] The price of the gum has had

[1] *New Zealand Official Yearbook*, 1900.

[2] Statistics of the Dominion of New Zealand, 1910.

[3] J. M. Bell and E. deC. Clarke, "The Geology of the Whangaroa Subdivision, Hokianga Division," *New Zealand Geol. Survey* (1909), p. 96.

a tendency to rise since its early production, on account of its increased use and the limited supply. In recent years the price has ranged from £50 to £70 per ton for the higher grades of gum.

Kauri gum is used mostly in the manufacture of varnishes as a substitute for copal and mastic. Formerly it was shipped mostly to England and America, but later much of it began to be used locally in New Zealand. Some of the clear transparent or translucent varieties are used as a substitute for amber in the mouthpieces of pipes, cigar and cigarette holders, and a certain amount is used for carving small ornaments.

Reports are often heard of the approaching exhaustion of the gumfields, but the production still keeps up. Many of the districts have been exhausted, but others have been discovered, and many of the forest regions in which "gumming" is prohibited on account of the injury it does to the timber, may become available later when the timber is cut. It is probable that for many years to come gum mining will be an important industry in New Zealand.

PRELIMINARY NOTES ON SOME IGNEOUS ROCKS OF JAPAN. V[1]

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V. POTASH-RHYOLITE

Introduction.—The rock is of limited occurrence, forming a hill called Manzōyama, with the height of 200 meters above the sea-level and the base-area of about 1.62 square kilometers, standing near the bay of Shimoda, which is situated at the southern end of the Izu Peninsula, projecting southward from the middle of the main island of Japan, and is well known as the port first visited by Commodore Perry.

The rock occurs as a lava-flow, not widely extended, but of considerable thickness. On the southwestern foot of the hill, a distinct prismatic jointing in the lower part of the lava can be observed. Its eruption was preceded by that of the so-called plagioliparite, and was followed by an enormous outpouring of andesitic rocks after a somewhat long interval. The eruptions of these rocks seem to have happened about the middle of Tertiary time. Tuffites derived from these rocks contain sharks' teeth (mostly *Carcharodon megarodon* and *Lamina* sp.), *Lithothamnium*, and several kinds of foraminifera. The age of the formation is considered as Miocene.

Petrographical characters.—Megascopically, the rock is characterized by its color, which varies from brownish-red to light reddish-gray with a violet tinge, which distinguishes it from other rocks occurring in the region. Its texture is indistinctly porphyritic, owing to the small size of the phenocrysts, from 1 mm. to 2 mm. in length. The only phenocrysts are feldspar crystals with

[1] Published by permission of the Director of the Imperial Geological Survey of Japan.

prismatic and tabular habits, scattered in an aphanitic groundmass. There are also well-defined prismatic or irregularly outlined cavities having the crystal form of hornblende, in which the mineral material is entirely altered to a dark-brown loose substance. Their sizes are usually smaller than those of the feldspar phenocrysts. In this rock-type, phenocrysts of quartz are entirely wanting. Flow-structure is a constant feature; sometimes red flow-lines are distinctly marked in the light-colored groundmass.

Under the microscope the porphyritic character is pronounced. Fairly numerous phenocrysts of sanidine and a very small quantity of magnetite are scattered through the hyalocrystalline groundmass. Needles of apatite and minute crystals of zircon occur as accessory constituents.

Sanidine phenocrysts, which are the only important constituent mineral, occur both in tabular and in prismatic forms, with more or less rounded outline. They are simple or twinned, and in many instances, inclose clouded patches of glass and minute crystals of apatite and iron ores. The characteristic cracks, sometimes filled with reddish-brown iron oxide, are also observed. It has a low refraction and low double refraction, and exhibits a very small optic angle, which is nearly zero. In a specimen of brecciated lava, the sanidine is entirely replaced by a colorless substance which is isotropic, and has slightly higher refraction than that of Canada balsam. From these characters, it appears to be opal.

The groundmass consists essentially of potash-feldspar and devitrified glass in nearly equal proportion though their relative amounts vary somewhat in different places. The feldspar is variable both in shape and size. Some of the crystals show a distinct prismatic form, commonly twinned, but others are irregularly outlined. The glass base is more or less densely clouded with reddish-black, opaque spots or rods, their presence affecting the color of the rock. In rare instances very minute flakes of deep reddish-brown mica can be detected among them.

Chemical characters.—The analysis of the rock, from the western foot of Manzōyama, was made by K. Yokoyama in the laboratory of the Survey. The result is given as follows:

	A	B	C
SiO_2	70.75	68.13	69.06
Al_2O_3	12.44	15.75	14.41
Fe_2O_3	2.66	1.60	1.89
FeO	0.79	0.74	0.54
MgO	0.08	0.45	0.39
CaO	0.39	0.27	trace
Na_2O	0.39	0.61	0.24
K_2O	11.51	10.54	12.33
H_2O	0.84*	1.90	0.96
TiO_2	0.53	0.31	0.24
P_2O_5	0.10	trace	0.08
MnO	0.09	....	....
SO_3	....	0.07	0.28
CO_2	....	....	0.24
Total	100.57	100.37	100.51

* Loss on ignition.

A. Potash-rhyolite from Manzōyama, Izu. K. Yokoyama, analyst.

B. Quartz-porphyry from Himmelberg, Bl. Lebach, Prussia, described by Weiss and Gebe. K. Boettcher, analyst.

C. Quartz-orthoclasite from Mutterbach. Masserthal, Thueringerwald, described by H. Loretz. Hampe, analyst.

The chemical character of the rock from Manzōyama is noticeable on account of the extremely high percentage of potash, from which it is seen that the sanidine is entirely free from isomorphous mixtures of other feldspars. The quartz-porphyry from Himmelberg and quartz-orthoclasite from Mutterbach, the chemical compositions of which are given in columns B and C, are quite similar to the rock from Manzōyama.

	A	B	C
Quartz	25.2	23.2	19.9
Orthoclase	67.8	62.3	72.8
Albite	....	5.2	2.1
Anorthite	....	1.4	....
Corundum	....	2.8	0.6
Acmite	2.8	....	....
Diopside	0.7	....	....
Hypersthene	....	1.1	1.0
Ilmenite	1.1	0.6	0.5
Magnetite	0.6	1.4	1.2
Hematite	1.1	0.6	1.1
Apatite	0.3	....	....
Total	99.6	98.6	99.2

From the norms, ratios are given as below.

	A	B	C
$\frac{Sal}{Fem}$	14.09	25.41	25.11
$\frac{Q}{F}$	0.37	0.33	0.27
$\frac{K_2O'+Na_2O'}{CaO'}$	∞	24.4	∞
$\frac{K_2O'}{Na_2O'}$	∞	11.20	32.75

The magmatic name of the rock from Manzōyama is lebachose, in which division only a few rock-analyses are so far known to belong. On account of the richness in potash, the writer distinguishes the rock as potash-rhyolite.

GRAVEL AS A RESISTANT ROCK[1]

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In a recent[2] number of the *Journal of Geology*, Mr. John L. Rich presents the thesis that "gravel, in its relation to the agencies of denudation, is under certain geological conditions a highly resistant rock. To these agencies it will, in general, offer greater resistance than ordinary igneous or sedimentary rocks, with a few possible exceptions."[3]

The writer is in accord with this general thesis; but the specific evidence presented in arriving at this conclusion is not wholly accurate, and certain deductions affecting the physiographic history of the region should in the writer's opinion be interpreted differently.

Mr. Rich divides his paper into three parts: (1) to point out the theoretical reasons for the resistant nature of gravel deposits; (2) to show, from an actual occurrence in nature, that the gravels do behave as the theoretical considerations would lead us to expect; and (3) to sketch by way of suggestion the normal course of development of topography in a region where alluvial fans of coarse material are accumulating at the base of mountains. It is especially with No. 2 that the following has to deal.

It is shown that a plain-like lowland lies between the northern edge of the gravel deposits and the high mountains to the north. This lowland is in places 100 feet below the base of the gravel south of it, and is crossed by the mountain streams flowing southward out upon the desert deposits.

To explain this feature Mr. Rich presents three alternative hypotheses: (1) The gravels may have been removed by erosion

[1] *Jour. Geol.*, XIX, No. 6.

[2] *Op. cit.*, p. 492.

[3] Published by permission of the Director of the U.S. Geological Survey.

from the area between their present limit and the mountains; (2) There may have been faulting by which the lowland was relatively lowered; or (3) The mountains may have been worn back and the lowland developed by differential erosion since the deposition of the gravel.

Mr. Rich adopts the latter explanation and presents evidence to show that No. 1 is impossible. I wish first to indicate wherein the statements used as evidence to disprove No. 1 are inaccurate, and second to show that a combination of No. 1 and a part of No. 2 is the more plausible explanation of the observed facts.

Mr. Rich says:

> Opposed to the first of these alternatives is the fact that the gravel plateau ends abruptly along a relatively straight line. There are no outliers of gravel between this general line and the mountains. It is highly improbable that streams flowing nearly parallel and not more than a mile apart should strip all signs of the gravels from the upper four miles of their course, while in their lower course, where they flow across the gravel plateau, they should be in relatively narrow valleys with almost no tributaries and should have done little more than to cut their way through the plateau without having been able to widen their valleys to any great extent (Fig. 2).
>
> A second objection is the fact that the line of contact between the gravels and the underlying rock slopes upward toward the mountains at such an angle that it would intersect the projected line of the plateau surface at a point not far within the present limit of the gravels (see Fig. 5). In other words, the gravels thin toward the mountains at such a rate that they would wedge out within a short distance from their present limit, and the lowland is accordingly developed in the bed-rock.

On that portion of the geologic map of the Silver City quadrangle shown by Mr. Rich two important outliers have been omitted. Their position is shown in Fig. 1, *a* and *b*. Still another outlier is present at *c*, which position was just off the western edge of the first map. Nor should it be said that the gravel plateau ends abruptly along a relatively straight line, for as shown on the map the edge of the gravel plain has many of the characteristics of an erosion border. Further, it is not "highly improbable" that streams flowing nearly parallel and not more than a mile apart should strip all signs of the gravels from the upper four miles of their course, for a point which has failed to be considered here, though it is mentioned in another place (p. 500, line 3), is that *an increased*

gradient near the mountain core probably existed; first, because such an increased gradient is normal, and second, because there is in this entire region strong evidence of post-Pleistocene tilting (due to faulting) in the north.

Next, the diagram, Fig. 5[1] (used as evidence in the argument that the gravels never extended farther mountainward), is misleading. By actual outcrop on the map it may be shown that the gradient of the gravel *base*, measured from a *ridge top* to a

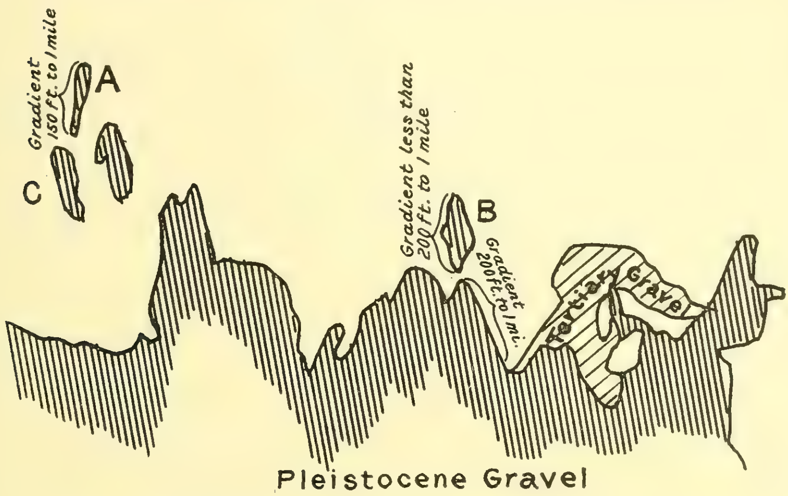

FIG. 1.—Showing irregular edge of gravel sheet and outliers north of it

valley bottom (the most favorable measurement), in places does not exceed 200 feet to the mile. The diagram shows a gradient of 1,500 ± feet to the mile. The long thin outlier north of Silver City has a basal gradient approximating 100 feet to the mile. The outlier on the extreme west has apparently a still lower gradient. The diagram is misleading because, with the low gradient that is shown above to exist, and with a gravel plain the top of which has an increasing gradient, the gravel might well have extended farther mountainward.

Further to cast doubt on the hypothesis that the mountain front once stood at the present position of the gravel edge and

[1] *Op. cit.*, p. 501.

that the gravels did not extend farther northward, the following facts are submitted. The lava series (composed of igneous sheets and interbedded gravel deposits at each locality of essentially the same character) is found north, northwest, northeast, southeast, and southwest of this area. A deposit of gravel belonging to this series actually underlies the Pleistocene gravel at the eastern side of the map (see Fig. 1). Besides these facts there is clear structural evidence, which need not be considered here, which leads to the inference that great lava sheets once *covered* this entire area, and that the gravel which now occupies this space at the surface is the débris derived from the denudation of the great up-faulted portions of these sheets, of which such masses as the Little Burro Mountains, Lone Mountain, and the Silver City Range are the remnants. From this it is logical to conclude that the present frayed northern edge of the gravels occupies its position, not because it represents an old scarp line, but because it represents a position of stability established by a number of factors—gradient, rainfall, favorable location with respect to drainage, etc.—all acting on a gravel sheet which originally extended farther northward. After the edge was eroded back to this position of stability, it is conceivable—in fact, is probable—that differential erosion carved out the lowland lying north of it.

To sum up: The gravels have been removed by erosion from a portion of the area between their present limit and the present position of the mountains, and the lowland has been developed *in the old floor* upon which these gravels once rested, by differential erosion.

SOME OBSERVATIONS AND EXPERIMENTS ON JOINT PLANES[1]

PEARL SHELDON

I

[1] This was done as part work for a Ph.D. degree at Cornell University. Acknowledgments are due to Professors R. S. Tarr and G. D. Harris for information and criticism.

I

INTRODUCTION

In an attempt to find the age of the joint planes of the Ithaca region with reference to the low folds which occur here, observations were made on 3,046 joints. Nearly all of these readings included both strike and inclination, although in a few cases one or the other was necessarily omitted. Over six hundred readings were made in the Fall Creek gorge at localities 55 to 58 and part of 54 in Fig. 7. For this distance readings were made on every accessible joint which was strong enough to show for two or three feet and not so variable that the data would be of little value. Occasionally observations were made on more poorly developed joints which were locally characteristic.

Although later work showed that this locality was hardly typical in some respects, this study showed how the joints of a single area vary with their strike and formed a basis for later work by showing which sets of joints are constant and strong and which too variable and weak to be of value in comparing different localities. During one summer and fall about two thousand readings, including this six hundred, were made in the Ithaca region. The following winter was given to experimental work and examination of the data already taken, and during the next summer another thousand readings were made in completing the section and investigating points connected with the theory, particularly the faulting.

Only a part of even the master joints could be read in the field but those were chosen which local observation and work in neighboring areas showed to be most characteristic for each place and, because of their constancy, most valuable for comparison with other areas. The work was begun without a conviction in favor of any one of the theories for the formation of joints and most of the evidence of their age was unexpected, so that the choice of readings was influenced little by preconceived ideas.

The data had a bearing on several points besides the age of the joints. The following are some of the results obtained:

Nearly all the uniform and strong joints fall into two groups.

Those in one group strike nearly parallel to the axes of the folds and form the strike set.

Those in the other group strike approximately along the dip of the rocks and are the dip joints.

The dip joints form two distinct, similar sets and appear to vary with the pressure which caused the folding.

The strike and dip joints are usually nearly vertical and a single joint varies little in strike and inclination at any exposure. The joints belonging to each set have a range in strike of only a few degrees at any one locality.

A set of joints making a moderate angle with the strike set is locally strong but these are not of the same character as the strike and dip joints. They are more variable in strike and inclination and usually have a greater hade.

Joints striking between the major sets are common but are usually weak and very variable with little apparent system. Their hade is usually large. In some localities the highly inclined joints are strong.

The master joints were evidently formed during the earlier part of the folding which took place here during the Appalachian Revolution. They are not younger than the faults which were formed at that time, since they are displaced by the faults. The hade of the strike joints shows that they were not formed before the folding. The dip joints vary with the folds and the forces active during the folding and were apparently formed at that time.

By compressing blocks of paraffin and resin various systems of cracks were obtained. Some were like those obtained by Daubrée. The finest cracks were nearly parallel to, and at right angles to, the pressure.

The observations support the shear theory of the formation of joints by indicating that the joints here were formed while shearing stresses were active and that the joints vary with those stresses. The joint planes, however, are nearly at right angles to the fault planes and are very unlike them, so that the theory that joints are incipient faults is not supported. Some factor like shock may have determined the position of the breaking planes which are classed as joints.

FOLDING

In general the rocks of the Ithaca region dip slightly to the south so that successively older strata are exposed to the north in the lake section. In the area studied the outcrops are Hamilton shale, Tully limestone, Genesee shale, and Portage sandstone and shale. The southward dip is not uniform, however. The region is crossed by a series of low folds which have been described and mapped by E. M. Kindle.[1] They have been more briefly described by H. S. Williams,[2] and one of them by S. G. Williams.[3]

In the Watkins Glen–Catatonk quadrangles the anticlinal and synclinal axes occur a few miles apart and their directions are usually somewhat north of east. The folds die out east of the longitude of Ithaca. Three of these axes—the Enfield syncline, Watkins anticline, and Corbett Point syncline—cross the Ithaca region. They are shown in Fig. 6, copied from *Folio 169*. The dotted lines represent approximate location. North of these axes and beyond the northern boundary of the area included in *Folio 169* is a well-developed fold which is conspicuous along Cayuga Lake because it is outlined by a prominent outcrop of Tully limestone. The point where the anticlinal axis crosses the western shore is accurately shown by a hard layer in the Hamilton shales which rises a few feet above low-water level at the highest point of the fold. The highest point on the eastern side is not so well shown but the direction of this axis as drawn in the upper part of Fig. 6 is correct to one or two degrees. It is a pitching fold. S. G. Williams gives the height of the Tully limestone outcrop on the west side as 160 feet and on the east side 235 feet above lake level. This has been called the Ludlowville fold and the Shurger Point fold.

From this axis the rocks descend to the northern limit of the map but the dip is not uniform. First there is a sharp dip, then a nearly horizontal region, then another steep dip to the north, thus forming a small fold on the northern limb of the main anticline.

[1] *Jour. Geol.*, XII, No. 4 (1904), 281–89; *Folio No. 169, U.S. Geol. Surv.* (Watkins Glen–Catatonk quadrangles), pp. 13–15; field edition pp. 98–107.

[2] *Proc. Am. Assoc. Adv. Sci.*, XXXI (1882), 412.

[3] *Am. Jour. Sci.*, 3d ser., XXVI (1883), 303–5.

The axis of the small anticline probably lies just south of the mouth of Taughannock Creek and the axis of the corresponding syncline about half-way between the mouths of Taughannock and Willow creeks. This fold is present on the eastern side of the lake but its axes were not determined there.

In the Inlet Valley the Watkins anticline is similar to the fold just described. It is represented by nearly horizontal rocks on the northern limb and inclined rocks on the southern limb. Further west, at Seneca Lake, the fold is stronger, with northward dips in the northern limb. South of the Enfield syncline is a strong anticline which reverses the dip.

In the area studied, therefore, there are three anticlines and three synclines with the Shurger Point fold the most strongly developed. The other two folds are represented by changes in the inclination of the beds without reversal of dip on each limb of the larger fold.

The dips of these low folds in southern New York range from 0° to 10° and are usually small. Though weak, the folds are persistent and are nearly parallel to the high mountain folds south of the Pennsylvania line. There seems no reason to doubt Kindle's conclusion that they were formed during the Appalachian Revolution. No folds of any other date are known here, so that the structure is comparatively simple. Broad warpings like that described by M. R. Campbell[1] apparently have not affected the problem of the joint planes.

FAULTING

Kindle[2] described a few small faults of variable character in the Watkins Glen–Catatonk quadrangles. G. C. Matson[3] mentioned several cases of movement along bedding planes and minor thrust faulting. He found that the dikes which cross some of these slipping planes were displaced, the maximum displacement given being two feet.

The ordinary type of faulting in this region is nearly horizontal

[1] *Bull. Geol. Soc. Am.*, XIV (1903), 277–96.

[2] *Folio 169*, p. 15; field edition, p. 108.

[3] *Jour. Geol.*, XIII, No. 3 (1905), 264–75.

thrust faulting with small displacement. These faults are numerous, occurring by the score in the shale beds, especially in the Hamilton shales. Often several may be seen in the height of a single cliff. Since these faults do not, as a rule, cross bedding planes the amount of movement is indicated only by the displacement of the joints, which are nearly at right angles to the faults. Whether or not this shows the total movement depends upon the

FIG. 1.—Two faults in the Hamilton shales. The eroded horizontal line is the lower fault. The upper fault descends to the left.

relative ages of the joints and faults. Perhaps some faulting took place before the joints were formed. The displacement is usually between a fraction of an inch and seven or eight inches. Four to six inches is common and a single outcrop of a fault will sometimes show progressive variation through almost the entire range of displacement found in these faults. In other places the displacement is nearly constant for rods.

One of the best faults seen in the Ithaca region is in the Hamilton shales where Salmon Creek falls over the Tully limestone back of Ludlowville. It passes around the base of the fall, just above the level of the pool, disappears beneath débris, then reappears and

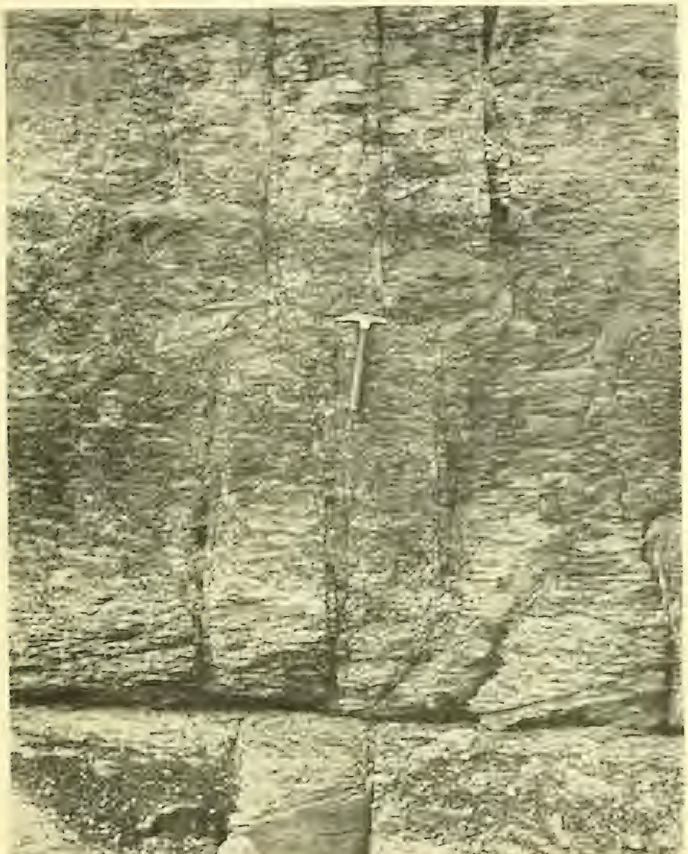

FIG. 2.—Right-hand continuation of the faults shown in Fig. 1. The head of the hammer shows the movement along the upper fault.

continues downstream just above the creek bed for many rods. It is made conspicuous by stream erosion along the fault line.

To casual observation these faults look like weak, slightly weathered bedding lines. Inspection shows the displacement of the joints across them and where they are exposed to stream or

wave cutting they appear as considerably eroded lines, sometimes worn into tiny caves. Figs. 1 and 2 show two of these faults in the cliff beside the bridge where the highway enters Ludlowville from the south. The photographs are of adjacent portions of the cliff. The lower, nearly horizontal, fault is eroded by the creek which is cutting the cliff. The upper fault, which has an unusually steep angle, has a fresh exposure and is therefore inconspicuous. The displacement along the upper line is shown by the head of the hammer. The movement has been such as to thrust the central wedge-shaped mass to the left and into the cliff between the upper and lower parts of the rock.

The exact direction of movement in the horizontal faults of the Ithaca region was not determined. Something might be learned from the relative amount of displacement of the different sets of joints but this method might be subject to error because of difference in the time of formation of the different sets. In the cases observed there was not a conspicuous difference in the displacements of the different sets, indicating that the direction of thrust made a fair angle with each set there present unless much of the movement took place between the times of formation of the different sets.

The comparative behavior of the faults in soft and hard rocks is interesting. In the Hamilton shales is a hard encrinal layer a foot or two in thickness. This is shown in Fig. 3. It did not yield to pressure without breaking so readily as the adjacent shales and the exposures of this layer along the lake show faults every few feet. They soon die out after entering the shale. Fig. 3 is a photograph of two faults at locality 14, Fig. 7. The slipping surfaces of the faults in this layer are much slickensided. The vertical displacement along these faults is from a fraction of an inch to three inches.

At locality 14, Fig. 7, where the encrinal layer rises above water level, the strike of eight faults was found to vary from N. 70° W. to due W. with an average of N. 76° W. At locality 39 in the same layer eight faults varied from N. 65° W. to S. 89° W., with an average of N. 72° W. The strike of the majority was from 20–25° north of west. At locality 9 where the encrinal layer passes beneath the lake level two readings were N. 86° W., two N. 84° W.,

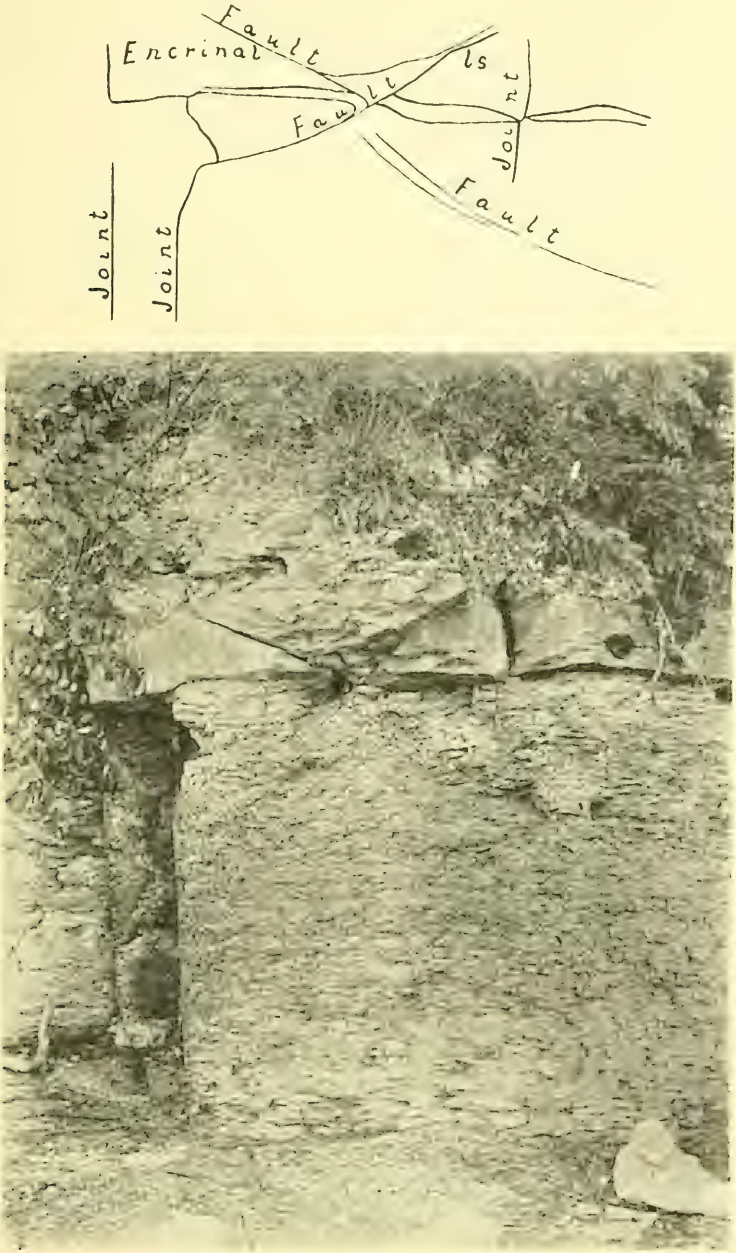

FIG. 3.—Symmetrical faults in the encrinal limestone

and one N. 80° W. These were the best seen for measurements, since one face of the faults had usually fallen away and the direction of movement could be read directly from the strong, even striations on the slickensided surfaces. Many other faults in this layer were seen but were inaccessible for measurement. The inclination of these faults is sometimes south and sometimes north and the angles are nearly the same in the two cases, making the faults symmetrical about a nearly horizontal plane. In the readings made the hade varied from 45° to 75°, but most were near the average, which was 62°. These faults usually continue for a few feet in the adjacent shale, but instead of continuing with the same hade they flatten out and become nearly horizontal as in the shales where no hard layer is present.

Since the faults of this region are usually nearly horizontal it might be expected that where well-developed bedding planes are present the slipping would take place along these. This is not true in the case of the encrinal layer. The unusually steep angle of the faults there seems to be due to the hardness of the rock, which has more influence on the location of the slipping planes than the presence of planes of weakness along the stratification. Some of the best of the horizontal faults were in nearly homogeneous shales, not along bedding planes. Evidently the bedding planes do not control the angle of the faults.

It is probable that the strike of the faults in the shales is about the same as that of the small faults in the hard layer which could be measured. It is noticeable that the strike varies from the direction of the axis of the fold by a rather large angle and that this angle increases eastward with the rise of the pitching fold. The faults were probably formed at the same time as the folds, that is, during the Appalachian Revolution, since no other disturbance of sufficient strength to produce these uniform faults is known here. The faults show that the direction of the local resultant force varied considerably from the general direction of the active force which produced the folds if the axes of the folds are at right angles to the latter. The explanation seems to lie in the pitch of the folds. Localities 9, 14, and 39 are in an anticline which rises rapidly to the east. The direction of movement points in toward

the center of a domed anticline looking from the south whence the active force came. Apparently the strike of the faults is about parallel to the strike of the rocks on the southern limb. If the pitching of a fold is due not to a variation in the active force causing folding but to a variation in the rigidity of the rocks, the molecular return forces in the soft rock near the center of the dome would not be so great as in the harder rock near the saddles and movement toward the dome might be expected. The exact analysis of the faulting is a problem in shearing closely connected with the shear theory of jointing.

OBSERVATIONAL WORK

JOINT PLANES

In measuring the joints a compass with a four-inch needle and open sights was used. The deflection of the needle from true north was taken roughly as seven degrees west. No attempt was made to read to less than a degree. The accuracy of the readings depended upon the character and exposure of each joint. The observations on most of the master joints were accurate to one or two degrees, but for the variable minor joints of large hade the error might be from five to ten degrees. The hade was measured with a six-inch protractor to which a lead was attached by a thread. Wherever possible the measurements of hade were made from such a distance that the edge of the protractor covered nearly the whole height of the exposure in order to obtain a good average. The readings were usually made to one degree. The master joint readings were mostly correct to one degree but for minor joints the error might be several degrees.

FALL CREEK JOINT PLANES

In the upper part of the Fall Creek gorge all accessible joint planes except the smallest and most variable were measured. Fig. 4 shows the orientation of these joints. The readings are tabulated by the method used by Professor Tarr for the joints of Cape Ann.[1] The strikes are divided into groups of three degrees,

[1] *Ninth Ann. Rep. U.S. Geol. Surv.*, 1887–88, pp. 583–88.

each beginning at the west so that the outer rays are N. 90° W.–N. 88° W. and N. 87° E.–N. 89° E. The figures in the margin give the number of readings to each group of compass directions. Fig. 4 shows that in direction the joints fall conspicuously into groups or sets. One set whose strike is usually between N. 70° E. and N. 80° E. is strong and nearly constant in direction and hade. Although the extreme readings of strike in this set vary by twelve or thirteen degrees the majority fall within four or five degrees. The hade is also nearly uniform. At locality 57, one hundred forty-six joints belonging to this set were measured. The total range of

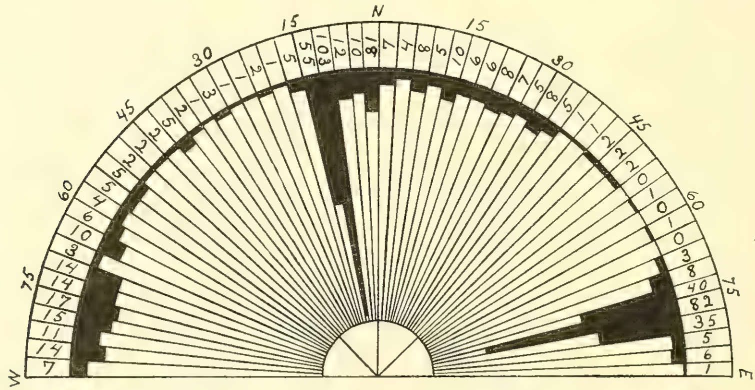

FIG. 4.—Tabulation of the strike of the Fall Creek joint planes

hade was from $6\frac{1}{2}$° S. to 9° N., but only two of the entire number showed an inclination to the south and most of those to the north fell within a range of a very few degrees. This set is well developed at Forest Home, locality 57, but not elsewhere in Fall Creek. Localities 55, 56, and 58 afford only a few readings and those not very good. This set is best developed in the shale beds, and the variation with the character of the rock may account for its presence at Forest Home, where shale beds are common, and its poor development in the more sandy layers above and below. The joints of this set strike nearly parallel to the strike of the rocks and form the set known as the strike joints.

Nearly at right angles is another set most of whose readings are between N. 10° W. and N. 15° W. They represent the set called

dip joints. These joints are strong, especially in the sandy layers, where they are conspicuous. As in the strike set, the hade is small and uniform. In a single small area the strike of the dip joints varies less, perhaps, than the strike of the strike set, but from place to place the variation is greater. Farther down the creek the average angle with the north is smaller. In upper Fall Creek there is little evidence of a second dip set, common elsewhere, which makes a small angle with the set just described. In Fig. 7, locality 55, is shown the average of some poor joints which may belong to this second dip set.

Besides these, certain joints with much more variable strike between 60° W. and W. might be considered as a set. In some places where the strike set is weak this set has a development which, though less regular than in the strike and dip sets, is quite strong and distinguishes the set from the mass of small joints. The hades are usually larger and less uniform than in the strike and dip sets. These joints are often curved and the smaller ones, especially at Forest Home, often show a sigmoid horizontal outcrop with the hade varying from one side to the other with the curve.

The rest of the joints of this area may be classed as weak and variable. For thirty degrees east of north the variable joints are more common and may be due to the tendency for a major set to form in that direction, but in the upper Fall Creek gorge they do not form a recognizable set. Variable joints a foot or two in length strike toward every point of the compass. Their hade is usually high, from 30° to 60°, and as a rule both the strike and hade vary over even the small extent of these joints. Enough readings were made on these to indicate their general character. They are common, but unimportant in comparing the variation of the joints with the folds.

The study in Fall Creek showed that joints of all directions are present but that those of different directions vary greatly in character. There are two sets in which the individual joints are strong and, what is more important, each joint is nearly the same throughout its extent and the joints of each set are nearly constant for one locality. It was apparent that these could be used in comparing different areas but readings on the variable joints would be of little

value. With these two sets belongs the second dip set found in other localities.

JOINTS OF THE ENTIRE REGION

Fig. 5 is a tabulation of all the strikes read throughout the Ithaca district, over three thousand in number. They are arranged in groups of five degrees each. It must be remembered that, with the exception of the six hundred also shown in Fig. 4, these joints were selected, so that the figure does not give a true record of the numerical occurrence of the various strikes but rather of the relative importance of the joints in each direction.

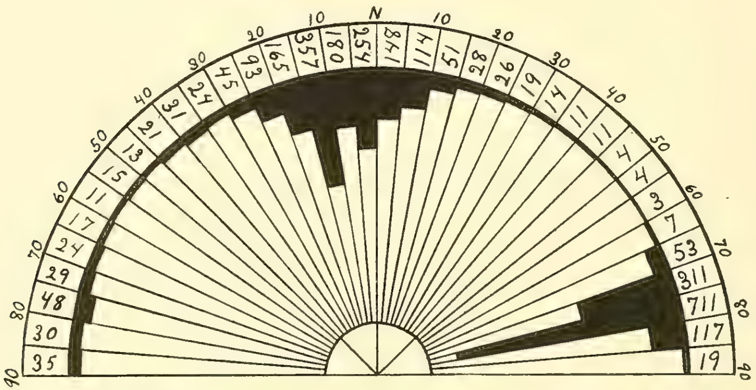

FIG. 5.—Tabulation of the strikes of the joint planes of the Ithaca region

STRIKE JOINTS.—In the Ithaca region the strike set is the most important. Fig. 5 shows that for the entire area studied far the greater part of all the joints which may be considered as belonging to this set do not vary more than ten degrees in strike. As the figure shows, there is almost no tendency for the strike set to grade into the minor joints at each side. This set is even more sharply defined and easily recognizable in the field.

The area studied was divided into squares of about a quarter of a mile on an edge. For Fig. 6 the readings of the strike joints in each small area were averaged together and the average is given beside a line drawn in the average direction. The center of the line is in about the center of the area considered and the width of the line is proportional to the number of readings included in the

average. A width equal to half a mile on the scale represents one hundred readings. Where the joints in any area vary in direction more than is usual in this set the average direction is given in light figures. Where the variation is less than usual the figures are heavy. It will be seen from Fig. 6 that the average directions are nearly parallel to the axes of the folds. It is noticeable that for the four localities along Salmon Creek, where this set is well developed, the average directions do not vary half a degree, though the individual readings vary by several degrees. There is a certain actual variation from place to place not due to the thoroughness with which observations were made. For example, just south of Crowbar Point and also on the opposite side of the lake the average angle is unusually low even though the number of readings is sufficient to give a reliable average. The cause of such deviations probably lies in the local variations of the forces producing the folds and joints. Near the Shurger Point anticline, which rises to the east so that the strike of the rocks is not parallel to the axis, the average strike of the joints does not turn so that it is parallel to the strike of the rocks, but in the opposite direction so that the strike of those south of the axis points slightly in toward the center of the domed anticline. Just how the strike joints vary with the pitching of folds cannot be determined from this one region. Further study of well-developed strike joints near pitching folds is necessary to warrant conclusions. In the southern part of the area studied the strike set is too poor to give reliable evidence.

Effect of the rock character.—The variation between the two averages near the mouth of Taughannock Creek is due to the character of the rock. The upper readings were in the Tully limestone, the lower in the Hamilton shales directly beneath the limestone. Few readings were made in the Tully elsewhere but a similar variation from the strike in the shales was noticed in other places. The hardness of the rock has a decided effect on the strike joints. They seem best developed in homogeneous shales, especially the Hamilton beds. This is partly indicated by the abundance of readings on this set in the northern part of the map. South of the lake the rocks are hard Portage sandstones and shales, and the meagerness of readings, though partly due to poorer rock out-

crops, fairly indicates the lack of development of this set. At Enfield Falls this set is fairly good and at Forest Home on Fall Creek it is well developed. The same effects may be seen in one locality. At Forest Home there are alternate shale and sandy layers. The strike joints are better developed in the shales and the dip joints in the sandy beds. If the contact between the two kinds of rock is sharp both sets often cease at the contact, the strike joints passing only through the shale and the dip joints only through the sandstone. In other places a change in hardness was found to affect the strike joints, sometimes causing them to cease abruptly.

Often where the strike set is poorly developed in the harder Portage beds the set striking a little north of west is unusually well developed, almost replacing the genuine strike set. This set appears mainly in the harder rocks. It is apparently not of the same origin as the strike set, since it is always less uniform even where stronger. This is well illustrated in Lick Brook where the conspicuous joints are the two dip sets and the westerly set. The westerly joints have a large hade and are not uniform but the strike joints, though few, are nearly vertical and more regular.

Hade of the strike joints.—In comparing the joint planes and folds more can be learned from the hade than from the strike. In Fig. 6 the second part of the statement of each average indicates the average hade. If the number is heavy it means that the angle of hade varied only a few degrees; if light, that the angle varied over ten or fifteen or more degrees. A light letter indicates that part of the readings were to the north and part to the south. A heavy letter means that nearly all were in one direction or the other, and the heaviest lettering that none were in the opposite direction. The average number is taken from the algebraic sum of the north and south readings.

In the region of the Enfield syncline most of the readings were slightly to the south, though only those at Enfield Falls were very reliable. At the southern border of the area the few readings taken were so variable that they averaged 0°. Between the axes of the Watkins anticline and Corbett Point syncline the strike joints are poor for reading of hade in most places. In many cases the outcrops do not permit a reliable reading and in most places the hade

is variable. Fig. 6 shows that many of the variable areas give averages to the south but the areas of greater constancy usually show averages to the north. The only really good area of strike joints in this district is at Forest Home. There, out of 146 readings only two were to the south. It is fair to assume that on the northern limb of the Watkins anticline the tendency is to the north.

From the axis of the Corbett Point syncline northward for about three miles the tendency is to the south. On the eastern side of the lake the readings are nearly all to the south from a point somewhat south of the axis of the syncline to a point about three-fourths of a mile north of Esty Glen (locality 43). On the western side the readings are more variable but the areas of more numerous and constant readings are strongly to the south. North of this is a region of variable joints on both sides of the lake. On the eastern side the three zeros represent one average of exactly zero and two averages of small fractions to the north. Just south of Shurger Point the readings are mostly to the south, north of Shurger Point they are variable with an average of about half a degree to the north. Just south of the anticlinal axis they are again nearly all to the south. Much the same thing occurs on the western side but there the northerly tendency predominates. Judging from the other folds a small change in the dip of the rocks, not sufficient to reverse the direction of dip or even to make the beds horizontal, might explain the behavior of the joints. Such a flexure might be local or a continuation of a fold dying out here. On the eastern side this turns the hades slightly to the north for a short distance but the general southerly tendency predominates. On the western side this flexure acts as if it merged with the main axis, either reversing the readings or making them variable from a point south of Crowbar Point to the main axis. Continued folding after the formation of the joints would also explain this irregularity. South of the axis of the fold the average hades to the north are so small that if the plane of the bedding instead of the horizontal were used as a datum plane the averages in most cases would be to the south.

North of the axis of the Shurger Point fold the hades are unusually uniform and satisfactory. Along the shore north of Salmon Creek the cliffs are talus covered and falling where acces-

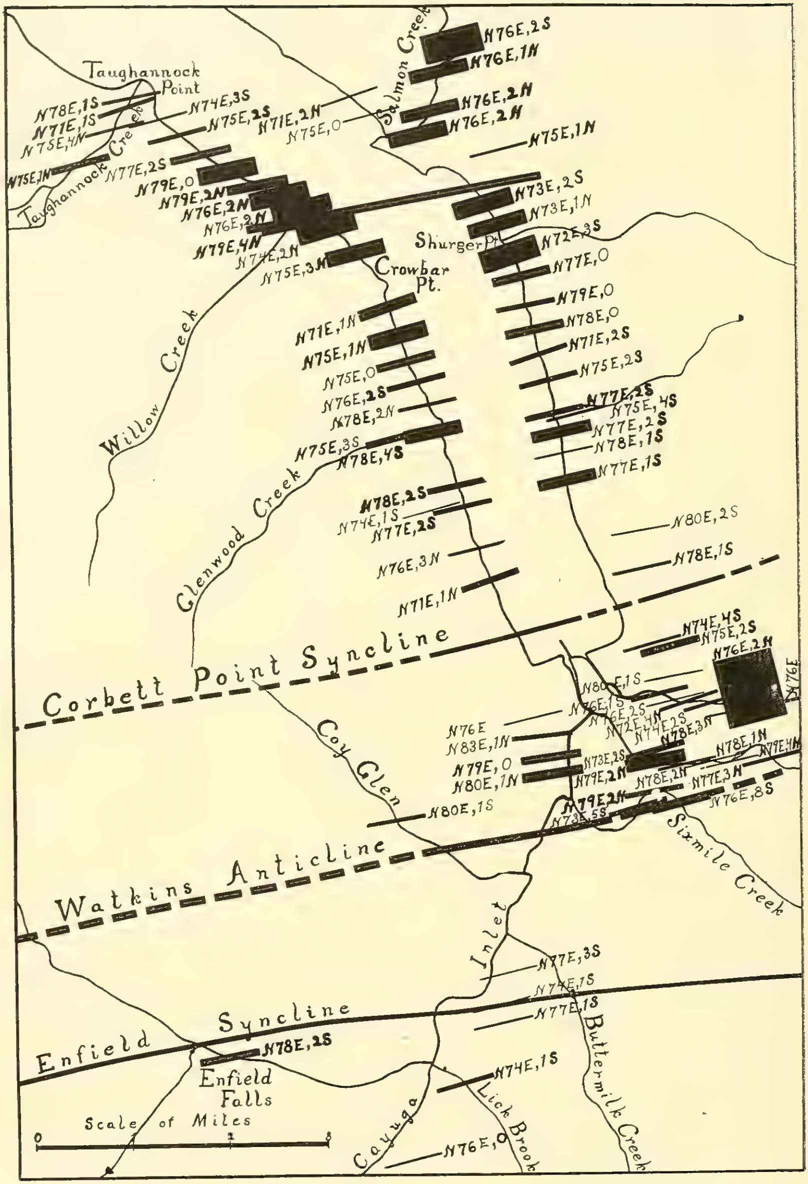

FIG. 6.—The axes of the folds and the average strikes of the strike joints

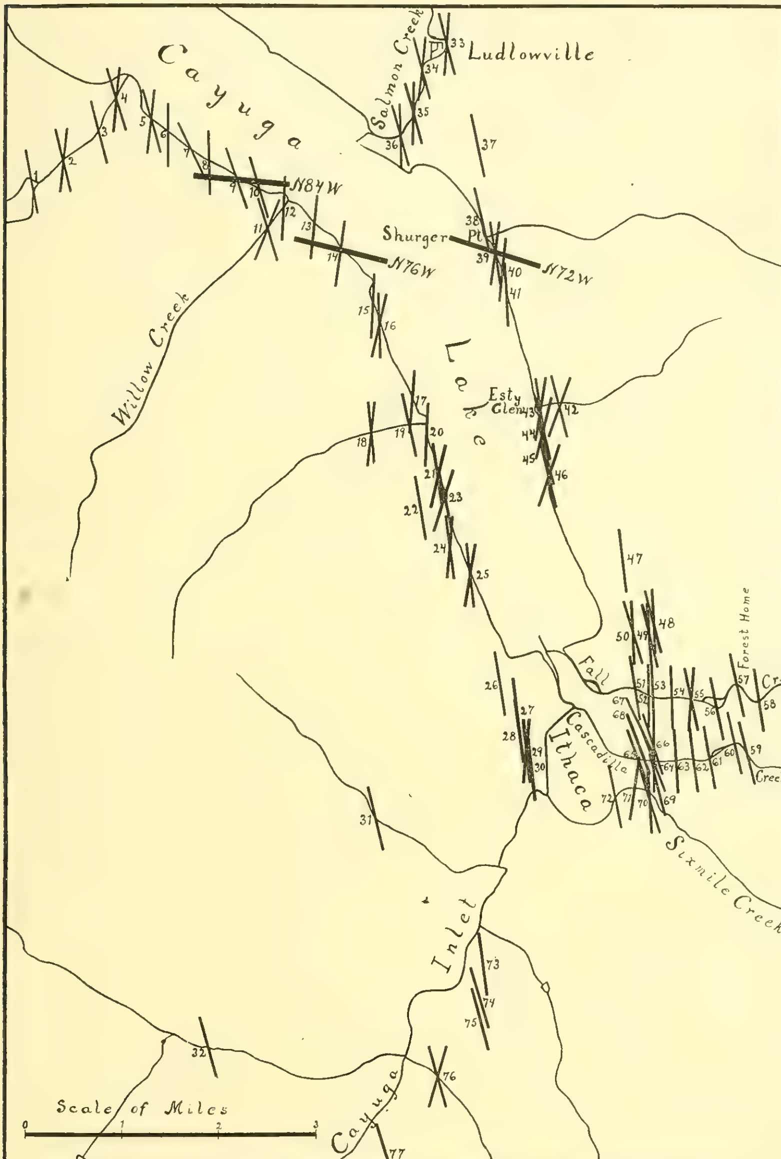

FIG. 7.—The strike of the faults and the average strikes of the dip joints

sible, so that the few readings made there are unreliable, but they are mostly to the north. On the eastern side of the lake the first area north of the axis and the first three in Salmon Creek show no readings whatever to the south, though the most northerly of the three shows a few zeros. Out of 61 readings at the fourth locality only one is to the north. There are a few zeros and the rest are to the south. Evidently there is a sharp reversal of the hade between the third and fourth localities. Because of a break in the rock wall at this point the transition only appears in the few variable readings at the adjacent localities.

On the western side of the lake no readings to the south appear for three-fourths of a mile north of Willow Creek. Then after an interval of transitional variable hades the readings are all to the south as far as Taughannock Point. The observations from the Taughannock gorge are not reliable for hade. Those in the lower part of the gorge are mostly from outcrops of slight vertical exposure, and near the falls (locality 2) the large amount of faulting and recent slipping make the readings untrustworthy. The hades just north of Willow Creek are small and are unusually uniform numerically. Between Willow and Taughannock creeks the reversal of hade takes place about where the dip of the beds changes from a strong dip to the north to horizontal. The steeper dip is resumed near Taughannock Point. On the eastern side of the lake a hard layer of rock was found to be nearly horizontal at the place where the hade of the joints is to the south but the variation in dip of the rocks was not traced. Evidently the sharp change of hade at the edge of Ludlowville is in a syncline.

Thus it appears that, in general, the inclination of the strike joints is in the same direction as the dip of the rocks or rather is such that, if the planes of the joints were produced, they would meet above anticlines and below synclines. The better developed the joints and more uniform the hade the more nearly true this is. Even folds not strong enough to reverse the direction of dip reverse the joints.

Dip Joints.—Next in importance are the dip joints. In the upper Fall Creek gorge there is a strong set of joints nearly at right angles to the strike set. In most of the other localities it was found

EXPLANATION OF FIG. 7

Locality	No. of Readings	Average Strike	Constancy	Average Hade	Constancy
1	4	N. 10° W.	High	2° W.	High
2	20	N. 14 W.	Low	5 E.	Low
	7	N. 5 E.	Fair	7 E.	Fair
3	4	N. 15 W.	Fair	1 E.	High
4	9	N. 17 W.	Fair	1 W.	High
	7	N. 5 E.	Fair	0	High
5	1	N. 16 W.	....	3 E.	....
	1	N. 6 E.	....	0	....
6	2	N. 1 W.	Fair	1 W.	Fair
7	9	N. 26 W.	Low	3 E.	Low
8	3	N. 2 W.	High	3 W.	Fair
9	7	N. 19 W.	Fair	0	High
10	10	N. 17 W.	Fair	0	High
11	6	N. 17 W.	Fair	3 E.	Fair
	7	N. 21 E.	High	0	High
12	4	N. 2 E.	High	1 W.	Fair
13	32	N. 5 E.	Fair	1 W.	Fair
14	25	N. 7 E.	Fair	2 W.	High
15	4	N. 2 E.	High	1 W.	High
16	12	N. 2 W.	Fair	2 E.	Low
	2	N. 12 E.	Fair	0	High
17	3	N. 3 E.	High	2 W.	Fair
18	20	N. 6 W.	Fair	0	Fair
	7	N. 5 E.	High	0	Fair
19	24	N. 13 W.	High	0	High
20	1	N. 1 E.	....	....	....
21	4	N. 9 W.	Fair	0	Fair
	5	N. 12 E.	Fair	1 W.	Fair
22	16	N. 10 W.	Low	6 E.	Low
23	10	N. 12 W.	Low	0	Low
	3	N. 16 E.	Fair	2 W.	High
24	4	N. 8 W.	Fair	0	Fair
	7	N. 3 E.	Fair	2 W.	Low
25	4	N. 7 W.	High	1 E.	High
	6	N. 8 E.	Low	2 E.	High
26	15	N. 10 W.	Fair	2 E.	Fair
27	21	N. 9 W.	Fair	3 E.	High
28	2	N. 10 W.	Low	7 E.	Low
29	8	N. 7 W.	Fair	11 E.	Low
	16	N. 3 E.	Fair	3 E.	Low
30	13	N. 7 W.	Fair	3 E.	Fair
31	3	N. 14 W.	Fair	1 E.	Low
32	8	N. 16 W.	High	1 W.	High
33	9	N. 14 W.	High	0	Fair
	78	N. 4 E.	Fair	2 E.	Low
34	5	N. 13 W.	Fair	1 E.	Fair
	19	N. 8 E.	Fair	4 E.	Fair
35	14	N. 15 W.	High	0	High
	22	N. 1 E.	Low	9 E.	Fair
36	2	N. 15 W.	Fair	9 E.	Low
	29	N. 1 W.	High	12 E.	High
37	6	N. 14 W.	Fair	1 E.	High
38	5	N. 15 W.	High	2 E.	High

EXPLANATION OF FIG. 7—*Continued*

Locality	No. of Readings	Average Strike	Constancy	Average Hade	Constancy
39	2	N. 9 W.	Fair	15 W.	Fair
	14	N. 7 E.	Fair	5 W.	Fair
40	6	N. 5 E.	Low	1 W.	Fair
41	6	N. 3 W.	High	1 W.	High
42	1	N. 14 W.	....	1 W.	....
	2	N. 19 E.	Fair	1 W.	High
43	6	N. 9 W.	Fair	0	Fair
	3	N. 8 E.	Fair	1 W.	Low
44	3	N. 14 W.	Fair	2 W.	High
	5	N. 13 E.	Fair	0	Fair
45	2	N. 15 W.	High	1 W.	High
46	22	N. 14 W.	High	0	High
	1	N. 17 E.	....	0	....
47	7	N. 8 W.	Low	0	Fair
48	1	N. 15 W.	....	4 E.	....
	5	N. 5 W.	Fair	3 W.	Fair
49	12	N. 14 W.	High	1 W.	Low
	8	N. 5 W.	Fair	3 W.	Low
50	1	N. 17 W.	....	1 E.	....
	3	N. 3 W.	Low	2 W.	Fair
51	17	N. 10 W.	Fair	1 W.	Fair
52	11	N. 3 W.	High	2 W.	High
53	9	N. 1 W.	Low	2 W.	Fair
54	91	N. 2 W.	Fair	1 W.	High
55	43	N. 12 W.	Fair	1 E.	Fair
	17	N. 4 E.	Low	0	High
56	5	N. 12 W.	High	0	Fair
57	109	N. 12 W.	High	0	High
58	16	N. 9 W.	Fair	1 E.	High
59	9	N. 14 W.	High	0	Fair
60	29	N. 13 W.	High	0	Fair
61	13	N. 11 W.	High	1 E.	High
62	25	N. 7 W.	Low	3 W.	Low
63	44	N. 5 W.	High	2 W.	Fair
64	15	N. 22 W.	Fair	1 E.	Low
	2	N. 2 W.	Fair	2 W.	Fair
65	51	N. 22 W.	Fair	0	Low
66	4	N. 19 W.	High	4 W.	Fair
67	19	N. 26 W.	Fair	9 W.	Fair
68	57	N. 22 W.	Fair	6 W.	Low
69	2	N. 15 W.	High	3 E.	High
70	22	N. 18 W.	Fair	12 E.	Fair
	9	N. 5 W.	High	0	Fair
71	1	N. 8 E.	....	2 W.	....
72	23	N. 12 W.	Low	14 E.	Fair
73	11	N. 9 W.	Low	2 E.	High
74	2	N. 18 W.	Fair	1 E.	High
75	2	N. 16 W.	High	2 E.	High
76	9	N. 15 W.	High	0	Low
	3	N. 15 E.	Low	9 E.	Low
77	1	N. 18 W.	....	2 W.	....

that the dip joints do not belong to a single set. They fall into two groups, with sometimes one and sometimes the other more prominent. Practically all the strong regular joints of small hade which do not belong to the strike set lie in the general direction of the dip of the rocks, but a curve drawn between the compass directions and the number of joints striking in each direction for a locality will usually show a tendency toward two maxima. That is, the dip joints form two groups with the average of one group nearly perpendicular to the axes of the folds, somewhat west of north, and the average of the other set farther east. There may be readings continuously between the two averages, or there may be a gap with no readings in the middle. There is a decided bunching of strikes toward the extremes rather than a larger number of readings near the average value of all the dip joints.

The strike joints show no such tendency. With them a curve between strikes and number of readings has a decided maximum near the median value with the number of readings decreasing rapidly toward the extremes. In one or two places strike joints were seen crossing each other, that is, fairly strong joints with directions near the extreme range for the strike set would occur at the same place and consequently intersect, but this is rare and the strike joints clearly form a single set. The dip joints often cross each other. In many areas only one dip set occurs, as is shown in Fig. 7. In such places it is usually found that the average of all the dip joints is about the same as one of the averages obtained by dividing the readings where both sets occur, thus justifying the division in the latter case. In better cases both dip sets occur together strongly and nearly equally developed, the two sets making so large an angle with so few intermediate joints that one would not consider averaging them together as a single set.

Around the city of Ithaca the more westerly of the dip sets is dominant. Northward the more easterly set is often the stronger. At Lick Brook the two sets are about equal and do not intergrade. With the set north of west they cut the rocks into conspicuous triangles instead of the more common parallelograms where only one dip set is strong. Southward from Esty Glen the dip sets are about equal, the angle between them is comparatively large, and each

set has only a fair range of strike so that the two are entirely distinct. The line of the cliff lies between the two sets and the cliff face is in many parts composed of projecting and re-entrant angles formed by the joint faces of large area meeting in obtuse angles. The small number of readings made in that locality is due to the fact that these joints are mostly at inaccessible heights in the cliff. The directions are rather constant, however, so that the readings made are representative of all.

The angle between the dip sets varies. Some of the averages in Fig. 7, which strike nearly north, come from observations too few in number to justify division into two sets. The resulting median value does not correctly represent either set if both are present. In other places, such as lower Fall Creek, there is a well-developed set whose average is nearly north, so that the angle between the two sets is only a few degrees. The upper locality at Willow Creek shows an unusually wide angle between the set. Those readings were made in the Tully limestone, and in the dip joints as in the strike joints the hardness of the rock seems to affect the direction. Unlike the strike set, the dip joints are better developed in the sandstones than in the shales. This appears where such layers alternate and also in the general distribution of the dip sets. In some of the softer shales along the lake they are rare and they are seldom so well developed there as the strike set. In the hard Portage rocks from the end of the lake southward the dip sets are far stronger than the strike. The conspicuous joints seen in the gorges in the city of Ithaca are dip joints.

The direction of the dip joints and the angle between the two sets seems to depend on the general force which caused the folding and the angle which the variable local resultant force made with it. The two sets seem to be arranged on each side of a line which is a compromise between the two. The range of the dip joints is from a line nearly perpendicular to the axes of the folds around to the east toward the perpendicular to the strike of the faults. The small angle between the sets near the city is probably related to the lack of strong folding there. In Fig. 5 the dip sets of the different areas overlap, obscuring their double nature.

Hade of the dip joints.—The hade of the dip joints is in general

larger and less uniform than in the strike joints. In some places in the Portage rocks where the dip joints are strong and occur at regular intervals, forming joint-faced buttresses along the gorge walls, the angle is quite uniform and nearly vertical. These evenly spaced joints occur in Fall Creek, Glenwood Creek, and in the Portage beds in the Taughannock gorge.

A detailed study of the pitch of the folds is necessary before the meaning of the hade of the dip joints will be clear. In general the hade of the joints and pitch of the rocks seem to be in the same direction, though some local measurements were opposite. The joints as a rule are not perpendicular to the bedding planes.

Some of the larger angles of hade are associated with faulting. This is true along University Avenue in Ithaca (localities 67 and 68). It is more conspicuous at Taughannock Falls where joints with a vertical exposure of two hundred feet or more are nearly vertical at the top of the gorge wall and bend to an unusually large angle with the vertical near the base where several nearly horizontal faults are present. This is probably due to drag along the faults.

Minor Joints.—Besides these fairly constant sets there are minor joints striking in every direction, but they are as a rule easily distinguished from the major sets by the fact that few of them are to be compared with the major joints in strength and especially by their irregularity and usually large hade. Near the Shurger Point anticline is a set of minor joints which are comparable with the major sets in strength. These joints vary widely in direction, but ordinarily make a fair angle with the strike and dip sets and always have a large inclination, from 30° to 60°. The strike is both N.E. and N.W. and the hade may be to either side in the joints of either direction. High-angled joints similar to these were seen in other parts of the area studied but usually not so well developed. In Salmon Creek highly inclined joints of about this strength are frequent but their direction is nearly the same as that of the regular strike set. In fact, some of them seem to be continuous with strike joints which are nearly vertical for part of their height, then suddenly bend to a high angle and probably change their direction somewhat also. Measurements on these

joints are only approximate because the exposures are usually poor. The rock walls quickly fall where these large diagonal planes for slipping are present. These highly inclined joints are not uniform in direction and a single joint is usually a curved instead of a plane face. They seem to be associated with the stronger folding.

Among the smaller joints of interest are certain offshoots from the dip joints. In an area where nearly all the dip joints belong to

Photograph by G. D. Harris

FIG. 8.—Jointing on the east shore of Cayuga Lake. The joints are not at right angles to the stratification but are inclined in the same direction as the beds.

one set but where there is an occasional example of the other set, or where the dip sets vary from their usual direction, the less usual joints sometimes have small cracks running off diagonally for a few inches in the more common direction of the dip joints.

Of the joints with no apparent uniformity perhaps the most interesting are the smallest. Some of the rocks, especially the Hamilton shales, are broken by a mass of tiny, smooth, curved faces of only a few inches in area. These are the faces along which the shale parts when it crumbles. They have no apparent system.

Joint planes are present in all sizes from an inch to two or three hundred feet in length and height but there is not an even gradation from one to the other extreme. The joints are divided into groups and each group shows distinct characteristics.

The strike and dip relation of the master joints of this region has been generally observed and readings have been made on the directions of the joints, chiefly by C. G. Brown whose data were used by Professor Hobbs.[1]

INFLUENCE OF JOINTS ON TOPOGRAPHY

The joint planes of this region have a marked influence on the form of gorges, cliffs, and waterfalls. The joints in the cliff along Cayuga Lake were made famous by the illustrations of Hall and Dana. Fig. 8 is a photograph of some of these joints at locality 46, Fig. 7. Their effects on gorges and waterfalls have been illustrated and described many times.[2] The rapidity of erosion seems greater where the strongest joints are transverse to the general stream direction rather than parallel to it. In the latter case small streams often follow a very narrow channel between two parallel joint faces. Where the transverse joints are strong and there are one or more sets nearly parallel to the stream, there are often broad chambers in the gorge with the walls formed by the larger joint faces and the stream entering and leaving by narrower openings. These may be seen in upper Lick Brook and in other gorges in the hard Portage rocks. The similarity between some of the larger features of drainage and the directions of the joint planes seems to be due to the fact that the streams were once consequent upon the same uplift with which the joint planes are associated.

[1] W. H. Hobbs, *Jour. Geol.*, XIII, No. 4 (1905), 363–74.

[2] R. S. Tarr, *Bull. Amer. Geog. Soc.*, XXXVII (1905), 193–212; *Pop. Sci. Mo.*, LXVIII (1906), 394–96; *U.S. Geol. Surv., Folio 169*, p. 3; field edition, pp. 24–25; *New Physical Geography; Physical Geography of New York State;* W. H. Hobbs, *Jour. Geol.*, XIII, No. 4 (1905), 363–74.

[*To be continued*]

Petrological Abstracts and Reviews

Edited by ALBERT JOHANNSEN

Craig, Wright, Bailey, Clough, and Flett. *The Geology of Colonsay and Oronsay, with part of the Ross of Mull.* Mem. Geol. Survey Scotland, No. 35. Edinburgh, 1911. Pp. viii +109; plates VI; figs. 21; map 1.

Colonsay and Oronsay are two small islands of the Inner Hebrides, lying between Islay and Mull, and are formed chiefly of schistose, metamorphic rocks of sedimentary origin and probably of Lower Torridonian age. They include limestones, phyllites, mudstones, banded flags, sandstones, feldspathic and epidotic grits, and conglomerates, and have a thickness estimated to be at least 5,000 feet. The rocks are much folded and show two series of cleavages, the earlier of which is slaty cleavage and is separated from the later "strain-slip" by a period of igneous activity, during which time there were intruded several small masses of syenite and diorite and numerous lamprophyric dikes. Subsequently a series of vogesites were intruded. No sediments are found intermediate between the Lower Torridonian and those of the Glacial period, the long interval being represented only by the igneous intrusions.

The igneous rocks consist of quartz-hornblende syenite, kentallenite, and augite diorite. There are two phases of the syenite; a marginal phase which is very basic and full of included bowlders, and an interior acid phase which is bowlder free. The marginal phase is a dark rock consisting of short, stout crystals of hornblende and a little biotite in a scanty matrix of feldspar (perthitic orthoclase, with albite in some places) usually micrographically intergrown with quartz. A peculiar feature of this border facies is the fact that it is crowded with bowlders of quartz and quartzite in all stages of assimilation, the unaltered portions being surrounded by halos of feldspathic material, usually potash feldspar and quartz with a little albite, formed by the combination of the dissolved silica with the basic magma. The "feldspathic ghosts" often retain the original shape of the bowlders and indicate the tranquillity of the process of replacement and the viscosity of the magma, the later being indicated also by the uniform distribution of the lighter quartz bowlders in the heavier magma. The authors say the rock can

best be described as hornblendite, passing into hornblende picrite in places, though differing from the normal types, which carry basic plagioclase, in that in these rocks the general feldspar is perthitic orthoclase with some albite. The rocks are intermediate between the syenites with which they are associated and the kentallenites. The influence which the included quartz bowlders have had upon the magma is shown in the local concentration of the alkalies around them. In the magma, which is predominantly hornblendic, the quartz bowlders are replaced by alkali feldspars and quartz. Calcium feldspars, such as one would expect in a calcic magma, are entirely absent.

The central acid phase of the intruded mass is quartz syenite, consisting of hornblende and less biotite in a matrix of feldspars, chiefly orthoclase with some albite, and quartz.

The kentallenite occurs in a mass about fifty acres in extent at Balnahard, and closely resembles the type rock from Kentallen Quarry. A porphyritic phase of this rock is also found.

Augite diorite, in the sense used by Hill and Kynaston, forms the largest outcrop of igneous rocks on the island. It is a black-and-white rock with about equal amounts of femag and feldspathic constituents. Under the microscope the rock shows a porphyritic texture with biotite, pale-green augite, some hornblende, and some pseudomorphs after olivine in a groundmass of about equal amounts of perthitic orthoclase and plagioclase—oligoclase and oligoclase-albite. (Query: porphyritic augite monzonite?)

The minor intrusions on both islands consist of dikes and sheets, and are lamprophyres, basalts, and a few felsites. The lamprophyres are all vogesites and generally strike in an east-and-west direction. The northwest dikes are olivine "dolerites" and monchiquites, the former being fine-grained dark rocks, rarely porphyritic or vesicular, of perfect ophitic texture, and consist of olivine, some biotite, zonal feldspars of labradorite with oligoclase rims in some places, and purple augite. The rock is a typical olivine diabase as the term is used in America. A variety of this rock but containing a considerable amount of analcite and zeolites occurs and of this the authors say it "may be described as analcite-bearing dolerite." To this rock the new name *Crinanite* is given. It is thus described:

The *crinanites*, then, are dark-coloured, fine-grained basic rocks consisting mainly of olivine, augite, and plagioclase felspar, with a considerable amount of analcite and zeolites. Olivine is abundant in small grains more or less altered to serpentine. The augite is always purple and is sometimes bluish

or plum-coloured; it is pleochroic . . . . and the extinction angle about 44°. The pyroxene in fact belongs to the variety usually described as titaniferous and much resembles that which occurs in many basic nepheline-rocks and teschenites. Chemical analysis proves that the crinanites are rich in titanium. . . . . The felspar has albite (rarely Carlsbad or pericline) twinning and belongs mostly to labradorite, though the outer zones are more rich in soda and may consist of oligoclase or albite. The iron oxides form irregular plates often fringed with small scales of dark brown biotite.

Most of these rocks have very perfect ophitic structure, and the augite occurs as small angular patches between the lath-shaped felspars or enclosing them. . . . . In a few specimens there are large corroded felspar phenocrysts consisting mainly of bytownite. Analcite and radiating clusters of zeolites fill up spaces bwteeen the felspars or occupy small rounded steam cavities. Perfectly transparent analcite is not uncommon, but often this mineral is turbid and granular with weak double refraction. The radiate zeolite appears to be mostly natrolite. Evidently these have been the last minerals to crystallise, and as the rocks are often very fresh, it is difficult to believe that they have originated from the decomposition of the felspar. They are more properly a pneumatolytic infilling of interstitial spaces during a period immediately following the crystallisation of the pyrogenetic minerals. Carbonates and chlorite are often associated with them, and veins of analcite and zeolites, easily distinguished by their low refractive indices, often ramify through the substance of the felspar.

In their composition and in the properties of their minerals these crinanites bear much resemblance to the teschenites . . . . but the teschenites are much coarser-grained, less frequently porphyritic and contain much more alkali felspar. The teschenites occur as large sills or laccolites, the crinanites as narrow vertical dykes which often can be followed for long distances in nearly straight lines. The crinanites in Colonsay show transitions to the camptonites, and are associated with monchiquites, some of which contain nepheline.

Monchiquite occurs in dikes and is composed of altered olivine, biotite, hornblende, and augite in a groundmass of analcite and carbonates. A nephelite ouachitite also occurs. The "felsite" dikes are described as "for the most part too decomposed for petrological examination."

The authors further describe the tectonics of the islands, their glaciation, and their economic resources.

In Part II the geology of the south part of the Ross of Mull is briefly described. The rocks here consist of metamorphosed sediments, intrusive granite and diorite, and dikes of vogesite, porphyrite, monchiquite, camptonite, "dolerite," and granophyre.

Albert Johannsen

DAY, ARTHUR L., AND SOSMAN, ROBERT B. "The Melting-Points of Minerals in the Light of Recent Investigations on the Gas Thermometer, *Am. Journ. Sci.*, XXXI (1911), 341–49.

This article brings under one cover the previously published determinations of melting and other transition points made on the gas thermometer. One table contains the determinations that are considered accurate and another those that are only approximate. A bibliography of the original papers in which these results appeared is added.

ALBERT D. BROKAW

IDDINGS, JOSEPH P. *Rock Minerals, Their Chemical and Physical Characters and Their Determination in Thin Sections.* Second edition, revised and enlarged. New York: John Wiley & Sons, 1911. 8vo, pp. xiii+617; figs. 500; and 1 colored plate.

The issue of a second edition of Professor Idding's book so soon after the first is an indication of its success. In this revised work but little change has made been in the first part; the insertion of a page and a half on pleochroic halos and the substitution of Michel-Lévy's recent, for his old diagram of extinction angles on combined Carlsbad and albite twins, being all. The second part is increased by 66 pages by the addition of about eighty minerals, chiefly those occuring in pegmatites and as segregated ores, representing extremes of magmatic differentiation.

ALBERT JOHANNSEN

LEBEDEW, P. "Experimentelle Untersuchung einiger binärer Systeme von Silicaten," *Annales de l'Institute Polytechnique Pierre le Grand à St. Pétersbourg*, XV (1911), 690–720, figs. 2+11.

This article is in Russian with a two-page résumé in German. The studies are devoted to a diopside-olivine system and an anorthite-wollastonite system. In the first the eutectic point is reached with 40 mol. per cent olivine; in the second with 30 mol. per cent anorthite. Freezing-point curves of mixtures are plotted. In the résumé no question is raised as to whether either of these systems is a simple binary system. In the opinion of the reviewer the second at least should be considered a ternary system—either a part of the CaO–Al_2O_3–SiO_2 system studied by Shepherd and Rankin, or of a $CaSiO_3$–$CaAl_2Si_2O_6$–Al_2SiO_5 system, neither of which is so simple as the diagrams and the German résumé seem to indicate.

ALBERT D. BROKAW

Loewinson-Lessing, F. "Ueber die chemische Natur der Feldspath amphibolite, *Annales de l'Institute Polytechnique Pierre le Grand à St. Pétersbourg*, XV (1911), 559–76. 32 analyses.

The article is in Russian with a three-page résumé in German. The author shows that the feldspar amphibolites do not all fall into the chemical type of gabbro or diabase. In his 32 analyses he recognizes the following types: Melaphyre, Essexite, Gabbro-Norite, Vogesite Tephrite basalt, Shonkinite, Diabase, Gabbro-syenite Basanitic magma, Camptonite, two transition types, and certain special types not represented by any known eruptive rock.

According to texture the feldspar amphibolites are divided into four groups as follows: glomeroblastic, microgranitic, hornfels structure, and anomalous porphyritic texture.

Emphasis is placed on the lack of identity of chemical type in the feldspar amphibolite group.

Albert D. Brokaw

Loewinson-Lessing, F. "Ueber eine bisher unbeachtet kristallochemische Beziehung," *Centralblatt für Mineralogie, Geologie, und Paläontologie*, Jahrg. 1911, pp. 440–42.

The writer recalls the fact that double salts and hydrates usually crystallize with lower symmetry than the respective simple salts and anhydrous bodies and proceeds to point out that such minerals as may be considered compounds of a silicate and a non-silicate have higher symmetry than the constituent silicate. As examples he cites: Nephetite is hexagonal, while noselite, sodalite, and hauynite are isometric. Albite is triclinic while marialite (albite+NaCl) is tetragonal. Similarly helvite, danalite, melinophane, leucophane, the melanocerite group, and certain other complexes of this sort all develop higher symmetry than their silicate constituent alone. Apparently the symmetry of the non-silicate constituent is neglected.

Albert D. Brokaw

Schneider, Karl. *Die vulkanischen Erscheinungen der Erde*. Berlin: Gebrüder Borntraeger, 1911. Pp. viii+272, figs. and maps 50. M. 12, unbound.

The author has compiled, from many scattered and sometimes not readily accessible sources, data on vulcanism; much of the information being here brought together for the first time. The presentation is chiefly descriptive, genetic explanations rarely being given.

Vulcanism is defined as that phenomenon by which juvenile materials are brought from the interior of the earth into or upon its crust. These materials are divided into three groups: "rheumatitische" (ῥεῦμα, to flow), or that material which was poured out in a molten condition, "klasmatitische" (κλασμα, broken, fractured), material that is angular, broken, or rounded, and "pneumatolitische," or gaseous material. Since observations of eruptions cannot always be used in determining the history of a volcano, a morphological, topographical, geologic, petrographic, chemical, and physical study of previous eruptions must be made of former lava flows. The author gives his objections to the application of local for specific names for certain phenomena, as is done in the nomenclatures of Seebach and Stübel.

The most striking feature of a volcano is its built-up cone, and it is upon a study of the various characteristic forms which may be easily correlated with ideal sections, and upon a study of the materials which built up these cones, and of the forces which produced them, that the safest and most positive classification can be built. Too little regard, says the author, has heretofore been paid to "klasmatitische" material and he proposes a classification based upon the forms of the hill produced by the erupted material. Yet the author's own statement that the klasmatitic material may become the sport of the wind or be carried off by rainfalls shows how the outlines of a volcano may be altered to a remarkable degree in different latitudes. This would invalidate the classification to some extent, for it is, after all, based upon the topographic forms produced by the materials not carried away. Neither does the classification take into consideration the gaseous emanations upon which the character of an eruption somewhat depends.

Seven different types of volcanoes are recognized according to size, structure, and form.

"Pedionites" are characterized by the great extent of their lava flows. No volcano of this type is known for certainty in historic times. The material is generally rheumatitic though some klasmatitic is found. The Deccan is an example of a pedionite.

"Aspites" are characterized by bases which are wide in proportion to their height. They usually have a crater on the summit and the material is generally rheumatitic. Mauna Loa is an example. Vesuvius is a pseudoaspite.

"Tholoides" have slopes of over 35° and are convex upward. Like the preceding, the material erupted is rheumatitic but the height of the cone is greater in proportion to its base. This form is characteristic of

the older volcanoes, and Puy de Dome and Puy de Sarcouy are typical. In modern times it is rare, the cone Georgious on Santorin being the only one known to form in historic times.

"Belonites" have much greater height than base. They are easily destroyed, consequently few remain, Pelée being the only one recently formed.

"Konides" are related to Tholoides in having an intermediate base relative to height. The flanks are always concave upward and the material is chiefly klasmatitic, though much is rheumatitic. In many cases there is a crater on the peak. It is the type of most recent volcanoes and Fujiyama is a good example.

"Homates" are characterized by an increase in base and a decrease in height but on the whole they are small in their dimensions. They all surround a crater with the slopes inside and outside about equal and concave upward. The material is usually klasmatitic. Many recent volcanoes are of this type and many such cones occur on, or in, the craters of konides. Monte Nuovo, Hverfjell in Iceland, and some of the piperno volcanoes of the Campi phlegraei belong here.

"Maare." These have usually been called diatremes. In typical form they are of elliptical cross-section and penetrate the older formations without having built up cones at the surface. These volcanic tubes are not rare since Tertiary times and are of several types, depending upon the force of the eruption. When the tubes extend straight through the surrounding strata the author classifies them as of the "Alb" type when the older strata are bent downward, at the sides, they form the "Fife" type, when they are bent upward at the sides, the "Cape" type. In the "Rez" type the strata are bent upward around the tube but the material does not reach entirely to the surface. These are Lachmann's hemidiatremes.

In tabular arrangement these forms may be grouped as follows:

Older	Rheumatitic forms	Older forms	Pedionite
			Aspite
		Younger forms	Tholoide
			Belonite
Intermediate	Rheuklastitic forms	....	Konide (Pseudoaspite)
Younger	Klasmatitic forms	....	Homate
			Maare

The cycle of activity appears somewhat as follows. In the full strength of a volcano's activity the material ejected is rheumatitic and a pedionite is formed. The activity gradually becomes less, and aspites, finally tholoides and belonites appear. Sometimes succeeding the aspite stage there is an alternation of rheumatitic and klasmatitic material, and konides are formed, the klasmatitic material forming homate cones during the process. Sometimes the intermediate konide stage does not appear and aspites are followed directly by homates or contain them in the later stages. When the activity decreases still further the pneumatolitic stage is reached and the cycle is closed.

The formation of pedionites, aspites, or konides extends through a long period of time, while homates and maares have a brief period of development. The explosive process can represent only a single act after whose conclusion the activity must be closed forever. Nowhere do other forms succeed tholoides or belonites, but pedionites and aspites are succeeded by younger forms. Konides always show, in their entire cone, the story of the altering forces. They often carry on their extinguished summits the youthful, rapidly built homates, the work of a short explosive outbreak. Since the sequence is never reversed, the subsequent history of a volcano can be predicted, and the close of a cycle is indicated by the form of its last outburst. A volcano cannot be considered as active simply because, like Monte Nuovo and El Nuovo, it has had an eruption within historic times. From the forms of these cones it is seen that they will never again be active. Other volcanoes, such as Tambora, Tarawera, and Krafla, which began their activity in Tertiary times, are to be considered extinct also, for their last eruptions were of klasmatitic material only. This fact is of significance when it is applied to such volcanoes as Adatura or Dekeyama in Japan which, while it has had no outbreak in 2,100 years, has during all that time given off considerable pneumatolitic exhalations. The last outbreaks, however, were klasmatitic, and the types are those of the closing cycle.

The forms, then, of the cones produced, give the key for the determination of the stage of a volcano's history. To say that a volcano, which has erupted within the knowledge of man, may again become active, or that one which has never within historic times broken forth is extinct, is to base the assertion upon insecure data.

Succeeding the discussion of the classification of volcanoes, the author gives a chapter on the volcanic formations of central Europe since the Tertiary, and considers the geographic distribution of the active volcanoes of the present time. The chief volcanoes and volcanic zones are described

and sketch maps of their locations are given in very complete form, running through fifty pages of the book. The volume is concluded with a catalogue of volcanoes which have been active within historic times. Three hundred and sixty-seven are recorded with their names, latitude and longitude, absolute and relative height, and dates of eruption. As the author says in his introduction, the observations upon which the determination of activity is based are of very unequal value. For example, it may be noted that in the United States Mt. Hood is recorded as having been active in 1854, 1859, 1865, and 1866; Mt. Baker in 1843, 1853, and 1859; Mt. Ranier in 1841, 1843, and 1894; and Mt. St. Helens in 1837(?), 1841, 1842, 1854, and 1889. The author does not give his authority for the dates of eruptions and there may be many other volcanoes listed whose activity is as doubtful as the American. Eruptions of Mt. Ranier and Mt. St. Helens within historic times are extremely doubtful. Mt. Baker may have been active in 1843, and smoke by day and a glow one night were reported to have been seen on Mt. Hood in 1907 from a distance of a number of miles. In no case, however, is there record enough to more than place the volcanoes of the United States in the doubtful list. While many references to the literature of different outbursts are to be found in the earlier chapters, it is to be regretted that a complete bibliography of the various eruptions is not given so that one might determine the relative value of the observations.

The presswork of the book is clean and good but its appearance is greatly marred by muddy half-tones and crude line drawings. Throughout the work the bibliographic references in general, are good and complete, and are given in footnotes.

Albert Johannsen

Smolensky, S. "Schmelzversuche mit Bisilicaten und Titanalen," *Annales de l'Institut Polytechnique Pierre le Grand à St. Pétersbourg*, XV (1911), 245–63; figs. 5+10.

These studies are devoted to melts of a $CaSiO_3$-$CaTiO_3$ system and a $MnSiO_3$-$MnTiO_3$ system. The first falls into Type III according to Roozeboom, having a minimum melting-point with 33.4 mol. per cent of $CaTiO_3$. The second falls into Type V, giving a discontinuous series of mix crystals having a eutectic point with 38.3 mol. per cent $MnTiO_3$. Curves of the two systems are plotted from experimental results. Attempts to study a similar system with barium salts were complicated by lack of knowledge of the polymorphism of $BaSiO_3$. The article is in Russian with a two-page résumé in German.

Albert D. Brokaw

WOLOSKOW, A. "Schmelzversuche über Bisilicate mit Sulfiden und Halogenverbindungen," *Annales de l'Institute Polytechnique Pierre le Grand à St. Pétersbourg*, XV (1911), 421–42, figs. 6; 4 photomicrographs.

The article is in Russian with a two-page résumé in German. Solidification curves were studied by means of a Kurnakow self-registering pyrometer. The results are as follows: $MnSiO_3+MnS$, eutectic with 6·85 mol. per cent MnS, 1130° C. $BaSiO_3+FeS$ gave rise to a liquation of FeS and $BaSiO_3$ containing 10 mol. per cent FeS. $BaSiO_3+BaS$, eutectic with 25 mol. per cent BaS, 1325° C. $BaSiO_3+BaCl_2$, eutectic with 8 mol. per cent $BaSiO_3$, 902° C. Solidification curves of various mixtures are given.

ALBERT D. BROKAW

WÜLFING, E. A. *Ueber die Lichtbrechung des Kanadabalsams.* Sitz. Heidelberger Akad. Wiss., Math.-naturw. Kl., 1911, 20 Abhandl., pp. 1–26.

Calkins (*Science*, XXX [1909], 973), compared the indices of refraction of Canada balsam with various minerals in 300 thin sections from one to eight years old, and found that in only one case out of a hundred did the index of balsam exceed 1.544. The lowest value obtained was between 1.535 ± 0.002. He gives 1.54 as a fair mean, and says it rarely has an index of less than 1.535 or greater than 1.545. Schaller (*Am. Jour. Sci.*, XXIX [1910], 324), with an Abbé-Zeiss reflectometer, found that uncooked balsam in sodium light had an index of 1.524, soft-cooked an average of 1.5387, as usually cooked an average of 1.5377, and over-cooked an average of 1.5412 with a maximum value of 1.543. Wülfing in the fourth edition of Rosenbusch-Wülfing's *Physiographie*, Vol. I, Part I, p. 150, gave the value of the index of balsam as ± 1.54, and in the same volume, Part II, p. 345, said it varied between 1.542 nearly to 1.550.

In the present paper Wülfing gives determinations made by comparison with minerals in thin sections prepared 30 to 40 years ago, and also determinations made with an Abbé-Pulfrich total reflectometer which had been tested, for weeks previously, for errors. On a collection of thin sections prepared by Voigt and Hochgesang 30 years ago the value $n=1.538 \pm 0.002$ in the central portions of the slides and at the borders, which had become yellow with age, $n=1.5416$. On other sections values

between 1.5330 and 1.5382 were obtained, the mean value being $n = 1.537 \pm 0.004$ In order to determine if there was any difference in the indices of the original balsam used, tests were made upon samples submitted by six different firms. Incidentally, in making these determinations, the values of the indices of refraction of certain minerals were obtained. It was found that chalcedony, when occurring in rather coarse fibers, is practically uniaxial and has indices $\alpha = \beta$ or $\omega = 1.530$, γ or $\epsilon = 1.538$. Hydrargillite has values for α and β considerably higher than usually given, at least equal to 1.57. In most cordierite, $\alpha = 1.534 \pm 0.003$, $\beta = 1.539 \pm 0.003$, $\gamma = 1.541 \pm 0.003$. Nephelite, so far as the indices are concerned, is of two kinds; nephelite from Vesuvius (nephelite I) has $\omega = 1.5418$ and $\epsilon = 1.5378$, while elaeolite from Hot Springs, Ark., has $\omega = 1.5466$ and $\epsilon = 1.5417$.

In regard to Canada balsam, the author concludes that the indices of the majority of the slides of the Heidelberg collection lie between 1.533 and 1.541, and in only rare cases do they reach 1.544 or fall below 1.533, both cases being due to fault of manufacture. Balsam which has turned yellow does not always have a high index, but all balsam when exposed to the air discolors, becomes brittle, and increases in index. The balsam protected by the cover-glass or by a crust of balsam may retain its sticky consistency and low index even after 40 years; it is therefore, altered only on the surface or at the border of the cover-glass. Commercial balsams are so uniform that in the preparation of thin sections the limiting values of the index need not fall beyond 1.533 and 1.541, and, with practice, should be between 1.534 and 1.540.

Albert Johannsen

REVIEWS

Grundzüge der Paläontologie. Von KARL A. VON ZITTEL. II. Abteilung. Vertebrata. Neubearbeitet von F. BROILI, E. KOKEN, M. SCHLOSSER. München und Berlin, 1911. Pp. 598.

Zittel's *Handbuch der Paläontologie,* the publication of which was completed nearly twenty years ago, marked the beginning of a new epoch in paleontology. And his compendium, or *Grundzüge,* the first edition of which was published in 1895, the English edition by Eastman in 1900–1902, has been of the greatest service to all students of the science. But the years that have elapsed since these editions appeared (and the English edition did not include the mammals) have greatly impaired their usefulness. The science of paleontology, and especially vertebrate paleontology, is progressing with such rapidity that even a few years leaves any text behind.

It is very doubtful whether other editors could have been found as competent for the present edition as Broili, Koken, and Schlosser. Additions and changes have been made with great conservatism, some will think with undue conservatism; but, in the opinion of the reviewer, conservatism here is a commendable fault, if fault it be. It will be time enough to accept the many new orders and suborders of vertebrates, the many changes in classification, which have been proposed in recent years when they shall have stood a longer test. In the past history of science the majority of such innovations are ultimately rejected.

Of the fishes, treated by Koken, six subclasses are accepted: the Placodermi, or Agnatha, Elasmobranchii, Holocephali, Dipnoi, Arthrodira, and Teleostomi. As regards the Arthodira the relations of which have been the subject of no little discussion in recent years, Koken rejects the evidence of Placodermi affinities and accepts those of the Dipnoi. "Die *Dipnoer* . . . . sind den *Arthodira* näher verwandt . . . . mit den *Placodermen* nicht so nah wie früher angenommen."

The revision of the Amphibia and Reptilia has been well done by Broili; one misses little that should be included in the work. The many new discoveries among extinct amphibia have been intercalated without change in the classification, notwithstanding the new schemes, especially those of Jaekel, which have been proposed—and which yet

await justification. Doubtless changes will be required at no very distant time, for the Lepospondyli, at least, as stated, are in a very unsatisfactory condition; but the present urgent need here as elsewhere among the ancient vertebrates is more facts, not more new theories.

Among the Reptilia, also treated by Broili, only one new order is admitted, the Parasuchia, concerning which there is now a unanimity of opinion; nor have additional suborders been admitted, perhaps unwisely, save the Chelonidea among the turtles. The union of the cotylosaur reptiles in the same order with the theriodonts seems ultra-conservative, and yet the reviewer must admit that there seems to be no broad line of demarcation in the series between the two extremes. The writer does not agree with Broili in his disposition of *Lysorophus* among the lizards, nor of *Placodus* and *Mesosaurus* among the Sauropterygia.

The treatment of the birds, by Schlosser, is essentially that of the Eastman edition, with minor changes.

Especially welcome is the part devoted to the mammals, including nearly half of the work. Dr. Schlosser's reputation as a mammalologist is deservedly high, and his views will have much authoritative value. The recent works by Osborn and Gregory are of the greatest value, but nothing can take the place of such a compendium as the present one, with its precise definitions and systematic arrangement. One is interested to observe that, in place of the twenty-eight orders of Osborn, Schlosser follows the usual classification of the placental mammals into the Insectivora, Rodentia, Chiroptera, Carnivora, Cetacea, Edentata, Ungulata, and Primates, while the Sirenia, Proboscidea, and Hyracoidea are grouped with the Embrithopoda under the order Subungulata, of African origin; and the chief groups of South American origin, the Typotheria, Toxodontia, Entelonchyia, Astrapoth eroidea, and Pyrotheria are included under the order Notungulata. He classes the Monotremata and Marsupialia under the Eplacentalia. The Multituberculata, including even the disputed *Tritylodon*, are classed as marsupials, against which Dr. Broom and the present writer have protested. One can scarcely conceive of the possibility of the immediate evolution of reptiles into marsupial mammals in face of the oviparous mammals existing today. Notwithstanding the evidences afforded by *Ptilodus* the writer, as a herpetologist, firmly believes that the early multituberculate mammals were oviparous, with all the essentially primitive characters possessed by the living monotremes in the pectoral girdle, genital apparatus, etc.

Many new figures have been added to the work, but some have been retained which should have been rejected. Some minor errors are noticeable. Dr. Dall will be surprised to see that he is cited on page 177 as a writer on extinct frogs! The edition as a whole is very welcome to every student of extinct vertebrates; we only regret that the English edition might not also be brought up to date and the mammals included.

S. W. W.

"Beiträge zur Kenntnis der Oligozänen Landsäugetiere aus dem Fayum (Aegypten)." By MAX SCHLOSSER. *Beiträge zur Paläontologie und Geologie*, XXIV (1911), pp. 51–167; Pls. IX–XVI.

Perhaps no discoveries of extinct animals in recent years have excited more general interest than those of the Oligocene of the Fayum in Africa, as first made known by Beadnell and Andrews and later by Osborn. The present contribution by Schlosser, based upon extensive collections made for the Stuttgart Museum, adds very materially to this interest. In it he describes and figures new creodonts and rodents, an insectivore, a bat, and three new genera of primates of especial interest. And our knowledge of the Hyracoidea is also materially increased by the addition of much new material—"so dass die Andrewsche Monographie auch für diese Gruppe volkommen veraltet erscheint."

Most interesting of his discoveries is the new simiid *Propliopithecus;* and but little less so are his new genera *Parapithecus* and *Moeropithecus*, the former representing a new family of anthropoids. *Propliopithecus* he believes has a direct genetic relationship with *Homo:* "Aber auch für die Ableitung der Gattung *Homo* und wohl auch der Gattung *Pithecanthropus* (wenn nicht mit *Homo* identisch) von den oligozänen Genus *Propliopithecus* besteht kein prinzipielles Hinderness, denn in den oben berücksichtigen Merkmalen hat die Gattung *Homo* mit *Propliopithecus* sogar entschiedene grössere Aehnlichkeit als alle lebenden Simiiden-Gattungen." And he thinks that the recognition of this African antecedent of *Homo* is to be welcomed as doing away with the necessity of resorting to eoliths as proof of the existence of ancient Man. "If now *Propliopithecus* is the direct ancestor of Man the impossibility of his making eoliths is evident, since *Propliopithecus* had probably only the body dimensions of a human infant, and that so small a creature could have used stones of the size of the usual eoliths no one will seriously affirm." In the evolution of the Hominidae, aside from the gradual increase in body size, there has been a shortening of the premolars, a

decrease in size of the canines, and a development of an arched form of the lower jaws. He complains that many paleontologists have not appreciated the law of increase in size as a fundamental one in evolution, but, if the mammalologists have not appreciated it, surely other paleontologists have.

As regards the relationships between the South American and the Old World and North American mammalian faunas he says: "While the other orders are already represented in the South American *Notostylops* fauna, we have to deal, especially in the rodents and primates, with new faunal elements which must have gone thither either in the Oligocene or at the beginning of the Miocene. And they could have gone only from Europe or northern Africa, since, as we have seen, these rodents are closely related to the European forms, and the primates have at least a closer relationship with those of the Fayum than with those of the North American Eocene. There must, therefore, have been a connection between South America and the Old World in the Oligocene or at the beginning of the Miocene." This theory has already been urged by Ameghino. "This connection could not have been a broad land bridge, otherwise there would have been an exchange of the larger mammals, which did not occur till the Pliocene." He suggests that this migration of the smaller animals may have occurred from island to island of an archipelago, the creatures possibly carried by the larger birds of prey. And he thinks also that about the same time there was a like exchange of the smaller mammals between North America and Africa.

S. W. W.

The Cid Mining District of Davidson County, North Carolina. By JOSEPH E. POGUE. Raleigh: *Bull. No. 22 North Carolina Geol. Survey*, 1910. Pp. 144; Plates 22.

This district is located in the central portion of the Piedmont Plateau and includes areas of slate, tuffs, volcanic breccia, rhyolite, dacite, and andesite, cut by gabbro and diabase dikes. All but the dike rocks range from a massive to a schistose condition with sericite and greenstone schists as the final product of dynamic metamorphism. The slates are interbedded with rhyolitic and dacitic tuffs. The coarser acid volcanic breccia grades into rhyolite flows and is thought to be a flow breccia. The gabbro dikes are approximately parallel to the schistosity and are cut by diabase dikes, said to be Triassic. The evidence as to the Triassic

age of the latter is inconclusive as it rests on the fact that they cut Triassic sandstones. On this evidence they might be post-Triassic.

The region comprises a series of folds, beveled to the present surface, and one great overthrust fault. The jointing, folding, faulting, and schistosity are referred to the same epoch of compression.

Four types of ore bodies are noted, namely impregnations in the schists, stringer leads in quartz, parallel to the schistosity, quartz veins cutting the schistosity, and replacement deposits.

The ore minerals are auriferous pyrite, chalcopyrite, galena, and zinc blend. The deposits are referred to magmatic waters, perhaps emanating from a granitic mass a few miles west. The time of deposition is placed after metamorphism. In view of Emmons' recent work in Maine and Tennessee the evidence on this last point needs to be more carefully worked out.

A. D. B.

The Iron Ore Supply of Japan. By KINOSUKE INOUYE. "The Iron Ore Resources of the World." Stockholm, 1910. Pp. 927–69; Plates 4; Figs. 13.

The iron ore deposits of Japan are classified in six groups as follows:

I. Magmatic segregations in granite. Not of economic importance under present conditions.

II. Bedded deposits usually in connection with radiolarian quartzites and slates of Paleozoic and Mesozoic age. The ores carry from 20 to 50 per cent iron with silica up to 40 per cent. They are usually rather high in phosphorus.

III. Contact deposits in limestone near contact with intrusives. These are the most important ores of Japan. The ore is chiefly magnetite with minor amounts of micaceous hematite and limonite. The iron content averages from 55 to 60 per cent with some analyses giving over 69 per cent. The ores are mixed with contact minerals and quartz and in some cases contain pyrite and chalcopyrite.

IV. Veins in various kinds of rocks. Not of great importance under present conditions.

V. Limonite deposits derived from the decomposition and redeposition of pyrite or magnetite deposits or by deposition from ferruginous springs. These are next in importance to class III.

VI. Alluvial deposits of iron sand derived from the decomposition of older rocks.

The amount of ore in sight is estimated at 19,000,000 metric tons;

probable ore, 37,000,000 metric tons, in addition to this amount. Low-grade ore, high in silica but of possible economic importance, 4,000,000 metric tons. A table of about 175 analyses of ores from various locations is added.

A. D. B.

The Iron Ore of Corea. By KINOSUKE INOUYE. "Iron Ore Resources of the World." Stockholm, 1910. Pp. 973–81; Plate 1.

Three types of deposits have been recognized, namely magmatic segregations, bedded deposits, and contact deposits, but little is known regarding the occurrence of the ores. The present output is about 70,000 metric tons per year, mostly limonite, with some hematite and magnetite. In one district a rough calculation gives 4,000,000 metric tons above level ground, but for the rest of Corea data are lacking. The producing mines are briefly described and a number of analyses are inserted. The iron content varies from 29 per cent in one of the contact ores to 70 per cent in one of the magnetite ores.

A. D. B.

Building Stones. By JOHN WATSON. Cambridge, 1911. Pp. 483.

This is a descriptive catalogue of the specimens of British and foreign building stones in the Sedgwick Museum, Cambridge, England. The rocks are grouped according to origin as igneous plutonic, igneous volcanic, metamorphic, and sedimentary. The sedimentary rocks are subdivided according to their geologic age. Under each of these divisions the rocks are taken up by countries and about half of the book is devoted to their occurrence, texture, and uses. The remainder of the book is the catalogue proper, giving the name and location of specimens by number. Brief notes as to color and texture, and in most cases chemical analyses and crushing tests are added.

A. D. B.

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FEBRUARY–MARCH, 1912

AN EXPERIMENTAL CONTRIBUTION TO THE QUESTION OF THE DEPTH OF THE ZONE OF FLOW IN THE EARTH'S CRUST

FRANK D. ADAMS
McGill University, Montreal

INTRODUCTION

In connection with an experimental study of the Flow of Rocks, on which the author has been for some time engaged and in which he has been assisted by grants from the Carnegie Institute of Washington, the question of the depth of the Zone of Flow beneath the surface of the earth has naturally presented itself. This subject has an interest and importance, not only as bearing upon many problems in geology, but also on one question at least of direct importance in mining, namely, that of the depth to which mineral-bearing fissures may extend in the earth's crust.

That the outer portion of the earth's crust was susceptible of subdivision into a Zone of Fracture and a Zone of Flow was set forth by Professor Heim in his great work *Untersuchungen über den Mechanismus der Gebirgsbildung*, and was based upon the data which he had obtained from his life-long studies in the Alps.[1] In this epoch-making work Heim states that as the result of his observations in the Alps he concludes that the upper surface of the Zone

[1] Albert Heim, *Untersuchungen über den Mechanismus der Gebirgsbildung*, Basel, 1878, Bd. II, 92.

of Flow for very resistant rocks, such as granites, is 2,200 to 2,600 meters or about a mile and a half below the surface of the earth, and considerably nearer the surface for limestone and other softer rocks. After thirty years of additional study Heim, in a recent paper, records his opinion that these depths are too small, that the Zone of Flow lies deeper within the earth's crust, but as to how much deeper he does not venture an opinion.[1]

President Van Hise in the interpretation of the results of his classic work on the ancient crystalline rocks of the United States in the district of the Great Lakes, reached a similar conclusion with reference to the twofold subdivision of the earth's crust, but placed the upper surface of the Zone of Flow at a considerably greater depth than Heim, namely, 12,000 meters or 7.4 miles.

Van Hise based his estimate on a mathematical calculation having as its starting-point the crushing weight of a cube of granite at the surface of the earth as determined by a testing machine in the ordinary manner adopted in testing the strength of building materials—granite being one of the strongest and at the same time one of the commonest rocks in the earth's crust. This calculation was made for Van Hise by Professor Hoskins who, taking the figures for the crushing strength of granite thus obtained, endeavored to calculate the depth below the earth's surface at which the pressure would be so great that all empty cavities would close as a result of plastic flow, even in the case of the hardest rocks like granite. This depth he fixed at four miles, or 6,520 meters. This is indicated by line "*a*" in Fig. 1. If however the cavities were filled with water Hoskins calculated that they would remain open to a depth of 6.4 miles, or 10,350 meters. This depth is shown by the line "*b*" in Fig. 1.

Van Hise then assumed an additional factor of safety, and took 12,000 meters as a depth at which not only all cavities would close but the hardest and most resistant rocks would flow—this being therefore the upper surface of the Zone of Flow in the earth's crust. This depth has been indicated by the line "*c*" in Fig. 1.

In order to make such a calculation, even in the very simple

[1] Albert Heim, *Geologische Nachlese*, No. 19 (*Vierteljahrschrift der Naturfor. Gesel. in Zürich*, 1908, 45).

case treated by Hoskins, certain assumptions must be made and the result obtained varies widely with these assumptions. Conse-

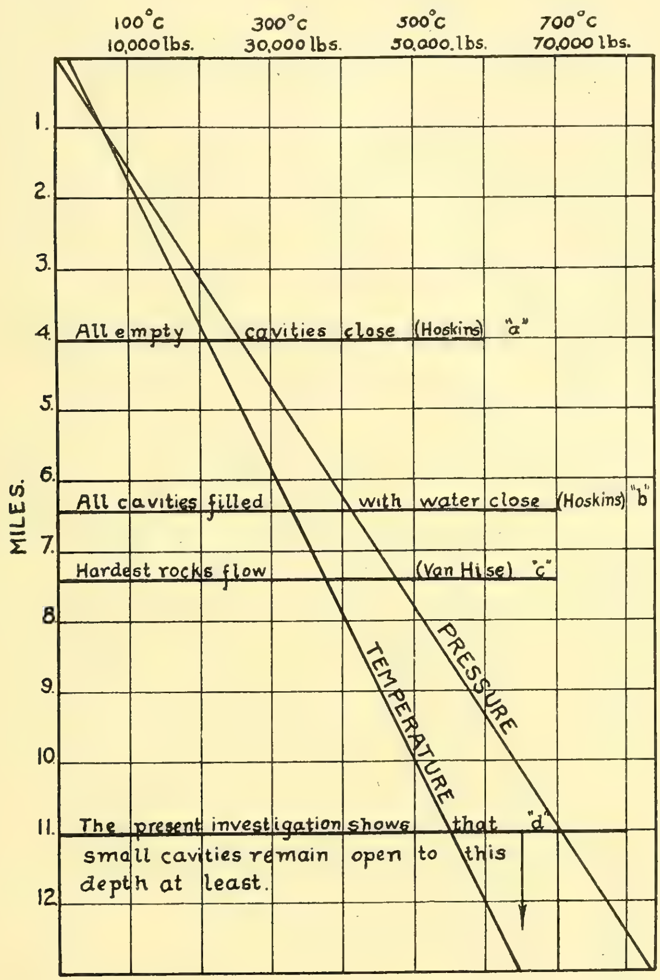


FIG. 1.—Showing the Pressures and Temperatures which are believed to exist within the Earth's Crust at successive depths to a distance of thirteen miles from the the surface. The temperatures are expressed in degrees Centigrade and the pressures in pounds per square inch. (see pp. 98 and 110).

quently, the figures obtained by Hoskins have not behind them the weight of a mathematical certainty. They are founded on

certain assumptions and have a probability no greater than the assumptions on which they are based.

The mathematical aspect of this question, however, as well as that of certain other questions arising out of the experimental results set forth in the present paper are treated at length by Mr. L. V. King, of the Department of Physics of McGill University, in the accompanying paper. As will be seen, Mr. King is of the opinion that the assumptions made by Mr. Hoskins are not permissible.

But even if the calculation were not based on these doubtful mathematical assumptions, a whole series of additional assumptions are made which very seriously affect the final result, as Van Hise himself points out. These are: (*a*) that rocks below the surface of the earth have the same strength as at the surface; (*b*) that the rocks constituting the earth's crust are all of the same kind; (*c*) that the temperature within the earth's crust is the same as that at the surface; (*d*) that the presence of water does not affect the character of the deformation; (*e*) that rocks yield as readily by fracture as by flow; (*f*) that rocks break as readily by fracture, when the deformation is slow as when it is rapid; (*g*) that the rocks whose crushing strength is taken as a datum are among the strongest in the earth's crust.

Van Hise believes that these assumptions are such that could we apply corrections for each of the factors concerned, we should find that these—with the exception of the first—"would tend to lower the figures given, that is to say, to bring the Zone of Flow nearer to the earth's surface." "But I suspect," he goes on to say, "that the various factors giving too great a depth are of far greater consequence than the one factor giving too small a depth."[1] He suspects the depth given by Hoskins is much too great, "probably twice too great."

The circumstance, however, that all these disturbing factors exist and that no account is taken of them in the calculation in question is frequently altogether forgotten and, consequently, positive statements are often made based upon this calculation, such as the following from a well-known book which has recently appeared.

[1] *A Treatise on Metamorphism*, 189.

We find that at a depth of about six miles beneath the surface the pressure must become so great that all rocks known to us would be crushed by it. If it were attempted, for example, to tunnel in rock at this depth, the roof of the tunnel would immediately collapse and the opening be entirely sealed up. The microscopic pores in the rock would likewise and for the same reason be closed.

As a matter of fact the figures for the depth of the Zone of Flow, which are under discussion, hang upon a slender thread of doubtful mathematical analysis enfolded by a cloak of many conjectures.

In his Presidential Address before Section G of the British Association for the Advancement of Science in 1904, Hon. Chas. A. Parsons discusses among other questions the possibility of sinking a shaft into the earth's crust to a depth of 12 miles, and in a letter which appeared in *Nature* (October 20, 1904) Geoffrey Martin expressed the opinion that at this depth the pressure would be so great that the walls of such a shaft, if it were constructed, would close in, owing to the viscous flow of the rock through which it passed. Parsons, in a note commenting on this letter, shows that a misplaced decimal point made the figures given by Professor Martin too high, and states that at the depth mentioned the pressure of the wall rock would amount to 44 tons per square inch, which in his opinion would be insufficient to close the shaft, adding:

I think that the evidence at present available leads to the conclusion that after a small amount of shrinkage of the shaft sides inward had taken place, a state of equilibrium would be established, enabling the surrounding rock in its state of great compression to withstand the so-called hydraulic pressure down to a depth from the surface of at least 12 miles.

He concludes,

It would however be interesting to subject a cylinder of granite or quartz rock carefully fitted into a steel mould and having a small hole bored through its center to a pressure of say 100 tons to the square inch and see what shrinkage in the hole would result.

As it seemed that important information might be obtained along the line suggested by Parsons, an experimental study of the question was undertaken, from which some rather interesting results have been obtained.

To go back for a moment to the important work of President Van Hise, it will be noted that in looking over the factors enumer-

ated by him as not having been taken into consideration, three are manifestly of much greater importance than the others in their bearing upon the depth of the Zone of Flow. These are: (1) the influence of pressure upon the rigidity of rocks in the deeper parts of the earth's crust; (2) the existence and influence of the higher temperature found at such depths; (3) the effect of long continued pressure as compared with pressure applied for short periods.

The other factors referred to are apparently of less importance. Thus the softer rocks—sandstone, limestone, etc.—occurring in the earth's crust do not extend to any considerable depth; the existence of water in the deeper parts of the earth's crust is a matter about which there is still a considerable amount of doubt; while it would seem that the strength of granite may be taken as fairly representative of that of the stronger rocks of the relatively superficial portion of the crust.

The question then arises as to whether it is possible, in approaching the question of the depth of the Zone of Flow from an experimental standpoint, to reproduce the conditions of rigidity, temperature and long continuance of pressure which exist in the earth's crust and thus give due value to these three hitherto doubtful factors in the problem. It would seem that this can be done approximately at least in the case of the first and second of these factors, but that it is practically impossible to accurately reproduce the third experimentally, for it is impossible in an experimental research to extend the duration of an experiment over decades or centuries. But even here some approach can be made to the reproduction experimentally of the conditions of this third factor, in the first place by extending the duration as much as possible, and secondly by the substitution of a relatively higher pressure during the shorter period within which the experiment is necessarily confined for the lower pressure existing in nature for longer periods, since a higher pressure during a shorter time will approximate at least in its results to the effects produced by a lower pressure for a longer time.

Before the attempt is made to reproduce the conditions of pressure and temperature which obtain within the earth's crust, it is necessary to form as clear a conception as possible as to what

these conditions really are. And here we are confronted with difficulties at the outset—for neither the pressure nor the heat existing as successive depths within the earth's crust can be calculated or otherwise determined accurately.

In order, however, to obtain some approximate measure of the pressure which exists at successive depths below the surface of the earth—and it is only the outermost portion of the crust extending to a depth of say 50 miles that comes into consideration for the present purpose—two assumptions, among others, will be made: (*a*) that the rocks composing the earth's crust are incompressible, and (*b*) that they are free from tangential stresses set up by the contraction of the earth's interior through secular cooling or by other causes. As a matter of fact, however, the rocks composing the crust are compressible and they are probably in most parts of the earth's crust in a state either of compressive or tensile stress. The first factor of compressibility, however, probably does not introduce any very serious error if omitted from consideration, but the second factor of tangential stress is more important and probably varies greatly not only at different points at or near the surface but at different depths below the surface. The data in our possession are inadequate to enable its influence to be calculated, but the investigations of Chamberlin, Woodward, Hoskins, and others[1] go to show that above the "Level of No Strain" great arches, if formed in the relatively cold surface crust, would be incompetent to sustain more than a small fraction of their weight and would thus collapse, tending to equalize the stresses in each successive zone.

For the purpose of this inquiry, the pressure at successive depths below the surface of the earth is assumed to be the weight of a column of rock equal in height to the depth in question. The specific gravity of the rock is taken as 2.8. These pressures are shown in Fig. 1.

It is also impossible to arrive at an accurate knowledge of the temperature within the earth's crust at successive depths below the surface. As is well known, the temperature gradient within the earth's crust shows considerable variations.

[1] See Chamberlin and Salisbury, *Geology*, I, 553 ff.

A careful study of these variations has recently been made by Königsberger and Mühlberg. According to these authors:

> It may be assumed that all over the earth in flat countries where the subsoil consists neither of comparatively recent eruptive rocks nor of deposits liable to change, there prevails a normal geothermic gradient. All deviations from the normal gradient are due to local influences: uneven surface of soil (mountains, valleys), the presence of great reservoirs of water (lakes, the sea), and heat producing processes in the interior of the earth or incompletely cooled eruptive masses.[1]

The average of the gradient of 32 borings in flat country in rocks which are neither of eruptive origin nor subject to considerable chemical alteration is given by Königsberger and Mühlberg as 1° Centigrade in 32.9 meters.

The geothermic gradient adopted as shown in Fig. 1 is based on this value.

The view that this temperature gradient continues uniformly downward in the earth's crust has been controverted by Strutt, who from investigations into the radio-activity of the rocks of the earth's crust concludes that the temperature rises uniformly to 1500°C., and then remains constant at that temperature to the center of the globe. This conclusion, however, does not affect the consideration of the present question, seeing that this temperature would not be attained until a depth had been reached which is much greater than those whose temperatures are made the subject of study in the present paper.

THE EXPERIMENTAL METHOD EMPLOYED

Two rocks were employed in this investigation and two series of experiments were carried out with each.

In the first series with each rock, the attempt was made to reproduce the conditions of pressure to which rocks are subjected at various depths within the earth's crust, both as to intensity and, as far as possible, as to duration; while in the second series of experiments the third element of temperature was also introduced.

[1] J. Königsberger and Mühlberg, "On Measurements of the Increase of Temperature in Bore Holes, etc." *Trans. Inst. of Mining Engineers*, London, 1910, XXXIX, Pt. IV, 9.

In every experiment a column of the rock, very accurately ground to the dimensions of .5 inch in diameter and 1.57 inch long, was taken and through it two holes were drilled. These holes were, as nearly as possible, .05 inch in diameter. One of these passed through the vertical axis of the column from top to bottom. The other passed transversely through the middle of the column, being at right angles to the other hole but a little to one side of it, so that the two holes did not actually intersect. A wire was then drawn to fit the hole exactly, so that the slightest change in the diameter of the hole could be detected by passing the wire into it.

A round bar of nickel steel, $3\frac{1}{4}$ inches long and $2\frac{1}{2}$ inches in diameter, was then taken and a hole very slightly smaller in diameter than the rock column was accurately drilled through it in the direction of the longitudinal axis. This bar was then heated slightly, and thus expanded just sufficiently to allow the column of rock to be slipped in so as to occupy a position in the middle of this bar or thick-walled tube. The tube was then allowed to cool. The perforated rock column enclosed in its steel tube is shown in Fig. 2. The rock was thus held firmly on all sides by the steel, but the size of the hole was such that the shrinking of the tube upon the column did not compress the rock more than was required to effect a perfect mechanical fit, and in this way to give the requisite lateral support to the rock when the latter was submitted to compression in a vertical direction. Preliminary experiments showed that this operation did not in the slightest degree affect the size of the holes which had been bored through the column, and also showed that if the latter were unsupported below, a load of 7,250 lbs. on its upper end would shove it down through the tube.

If the experiment was to be conducted at ordinary temperatures, a disk of paper was then placed on either end of the column to equalize the pressure and two pistons of hardened "Novo" steel, ground so as to pass easily into the ends of the tube were inserted, by means of which pressure could be brought to bear upon the enclosed column. The whole was then placed in a powerful press and the enclosed rock submitted to a pressure equivalent to any required depth beneath the surface of the earth for a period

varying from a few hours to two and a half months. Upon the conclusion of the experiment, the apparatus was removed from the press; the pistons, which could be readily withdrawn, as well as the disks of paper if any had been employed, were removed. The question as to whether the vertical or longitudinal hole had under-

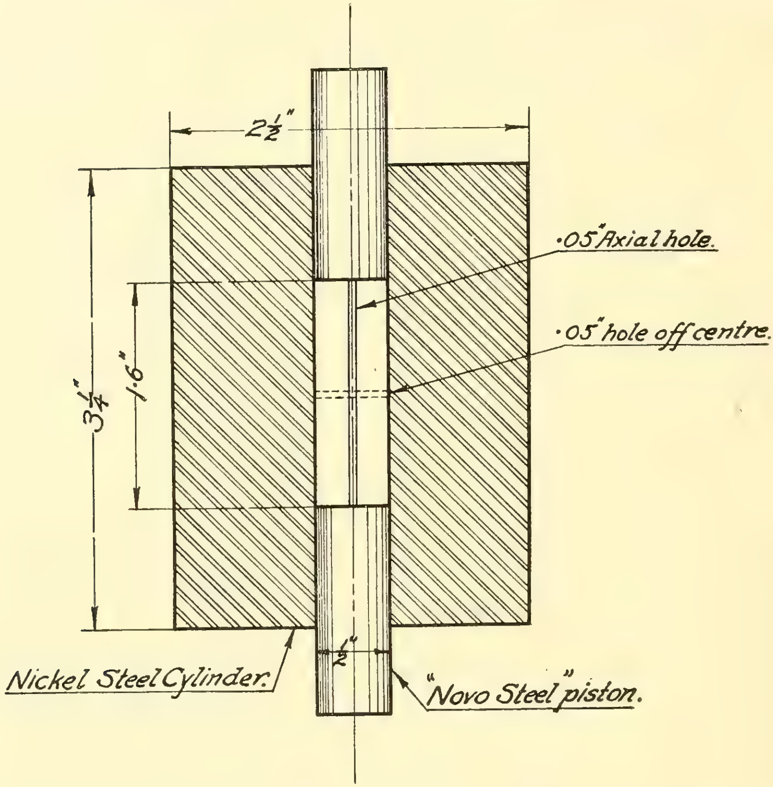


FIG. 2.—Showing the Column of Rock with a vertical and a transverse hole drilled through it, enclosed in a heavy tube of nickel steel.

gone any constriction was determined by ascertaining whether the wire would still pass through the hole which it had been drawn to fit, the slightest change in size being readily detected. The steel tube with its enclosed rock column was then placed in a lathe and the steel surrounding the middle portion of the column was turned off until only a film remained. This, where it covered the

ends of the transverse hole, was then removed, and the question as to whether there had been a constriction of the transverse hole was determined by attempting to pass the wire through it.

In those experiments in which the element of heat was introduced, the tube with the enclosed column was placed before compression in a suitably constructed apparatus in which it could be maintained at a constant temperature, during the experiment, the temperature being measured by a properly calibrated thermo-electric couple.

For the purpose of experimental investigation, it was important to select rocks which not only represent the chief types composing the earth's crust but which also possess physical characteristics which render them suitable for experimental purposes, that is to say, rocks which are massive, rather fine in grain, uniform in character, and free from cracks and other flaws.

Two rocks which fulfil these conditions excellently are:—(1) the Lithographic Limestone from Solenhofen, Bavaria; (2) the Red Granite from Westerly, Rhode Island.

LITHOGRAPHIC LIMESTONE, SOLENHOFEN, BAVARIA

This may be taken as representing the softer sedimentary type of rocks which are found more abundantly at or near the surface in the upper portions of the earth's crust. The Solenhofen limestone is very fine in grain, very massive in character, and of a buff color. It breaks with a splintery or choncoidal fracture, and Heim speaks of it as one of the most brittle of rocks. A chemical analysis showed that the variety employed in these experiments consisted of carbonate of lime holding 3.52 per cent of impurities. It has a specific gravity of 2.603 when dry and is slightly porous, as shown by the fact that when allowed to remain under water in vacuo for 24 hours it absorbs 1.63 per cent of water.

In order to ascertain the crushing strength of the rock as determined in the manner usually employed in the case of building stones, etc., a series of six 2-inch cubes were very carefully sawn out of a block of the limestone, and having been accurately ground, were tested in compression, observing all the precautions required to attain the most accurate results. These determinations were

carried out in the Testing Laboratories at McGill University, a 100-ton Wicksteed machine being employed, and gave the following results:

40,600	lbs. per square inch
28,400	" " " "
29,635	" " " "
33,788	" " " "
32,725	" " " "
32,750	" " " "
Average = 32,980	

The average crushing strength of the Solenhofen limestone is, therefore, 32,980 lbs. per square inch. It is thus seen to be an extremely strong rock; stronger, in fact, than an ordinary granite under compression.

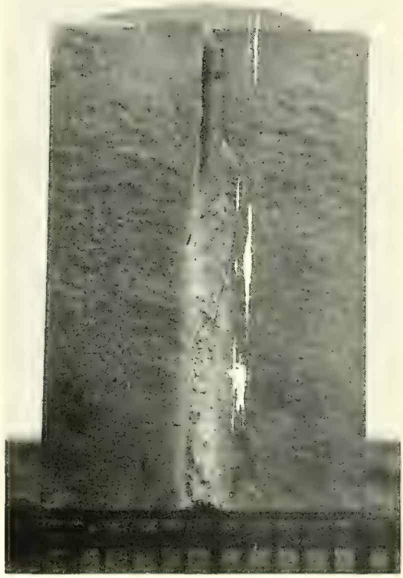
Four experiments were first made with columns of Solenhofen limestone, the pressure being increased in each successive experiment so as to represent successively greater and greater depths within the earth's crust, the element of time being also varied. These experiments were all, however, conducted at the ordinary temperature. The results are shown in Table I on p. 109.

It will be seen from these experiments, that at the ordinary temperature no trace of movement could be detected in the rock at a pressure equivalent to a depth of 15 miles below the earth's surface, even after the pressure had been continuously applied for two and a half months. When, however, the pressure was increased to that which is supposed to exist within the earth's crust at a depth of 20 miles below the surface, the experiment being continued for two and a half months, a certain movement was observed. At a pressure representing a depth of 30 miles and to a still more marked extent at a pressure equivalent to a depth of 40 miles, movements had taken place in 7 hours which resulted in the partial filling of the holes passing through the column. As will be noted, a depth of 31 miles represents a pressure of 100 tons to the square inch.

It is thus seen that Solenhofen limestone at the ordinary temperature and under conditions of cubic compression—which are the conditions of pressure to which it is subjected in the earth's

a

b



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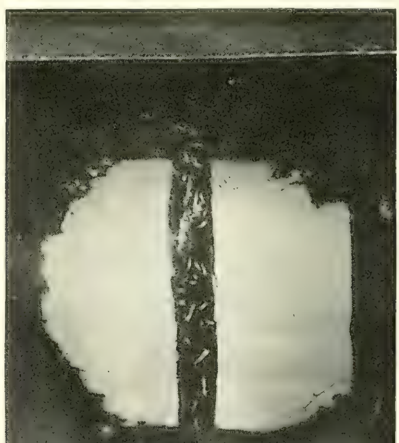

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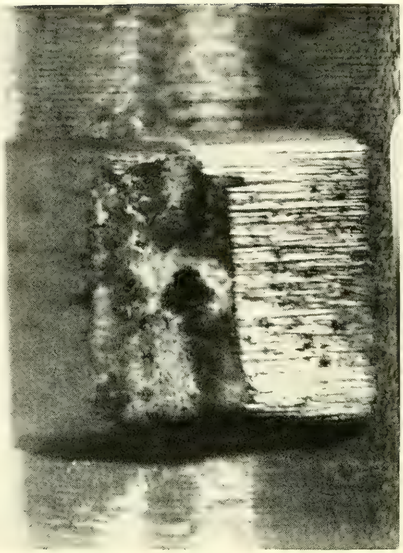

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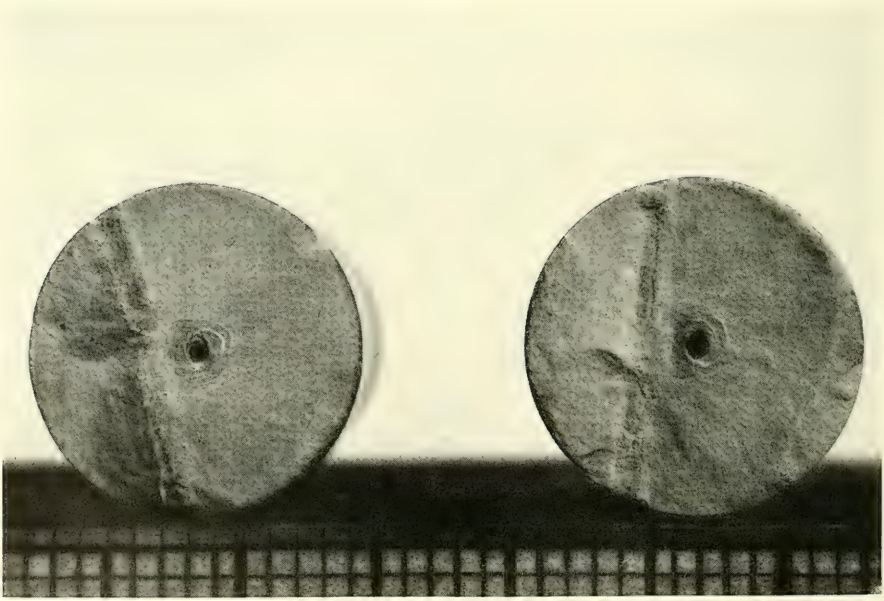

c

crust—will retain its form and will not flow into holes traversing it even when submitted for months to a pressure three times as great as would suffice to crush it instantly under the ordinary conditions obtaining at the surface of the earth.

TABLE I

SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF SOLENHOFEN LIMESTONE—AT THE ORDINARY TEMPERATURE—ARE SUBMITTED TO PRESSURES EXISTING AT SUCCESSIVE DEPTHS WITHIN THE EARTH'S CRUST

No. of Experiment	Pressure Pounds per Square Inch	Kilos. per Sq. Cent.	Depth below Surface of the Earth Represented by the Pressure	Duration of the Pressure	Results
359......	96,000	6,750	15 miles	$2\frac{1}{2}$ mos.	No movement of any kind. (See Plate I, Fig. *a*)
360......	128,000	9,000	20 miles	$2\frac{1}{2}$ mos.	Transverse hole smaller. Vertical hole partly filled. (See Plate I, Fig. *d*)
382......	193,000	13,570	30 miles	7 hrs.	Transverse hole unaltered. Vertical hole partly filled.
520......	200,000	14,060	31 miles	$\frac{1}{2}$ hr.	Transverse hole flattened. Vertical hole mostly filled. (See Plate I, Fig. *b*)
383......	257,000	18,070	40 miles	7 hrs.	Transverse hole flattened. Vertical hole mostly filled. (See Plate I, Fig. *c*)

The movement noted in the cases of experiments 520 and 383—representing depths of 31 and 40 miles—seems to be of the nature of flow, so far as it affects the transverse holes, these holes becoming flattened. But as shown in the descriptions of Plates I and II, the movement takes place by the development of minute fractures along the course of the vertical holes, small fragments of the rock becoming detached from the walls. The author desires to express his thanks to Dr. J. A. Bancroft of McGill University, to whom he is indebted for the photographs from which these prints were taken.

A second series of experiments was then made with a view to ascertaining the effect produced by the introduction of the factor of heat.

According to the investigations of Debray,[1] the highest temperature to which calcite can be submitted in open vessels without decomposition is 450°C. This is the temperature which is supposed to exist at a depth of nine miles below the surface of the earth.

Perforated columns of the limestone, identical in size and shape with those employed in the first series of experiments, were enclosed in heavy tubes of steel as before. The tubes having been heated to a temperature somewhat higher than 450°C., the column was inserted and the tube then allowed to cool and contract about it. The steel pistons were inserted in the usual manner and the whole being placed in a specially constructed heating apparatus, the rock was maintained at a temperature of 450°C. while submitted to the required pressure.

An investigation into the relative expansion of the nickel steel and the Westerly granite carried out by N. E. Wheeler, B. Sc. of the Department of Physics of McGill University, shows that with a gradually rising temperature the granite at first expands more slowly than the steel and then more rapidly.[2] The expansion curves intersect, i.e., both materials expand equally at a temperture of 400°C., and with the temperature of 450°C., at which all the experiments with two exceptions were conducted, the difference in expansion of the two materials is extremely small, the expansion of the granite being slightly greater, which serves only to cause the enclosing tube to hold the granite column a little more firmly.

As it was impossible with the apparatus employed to maintain an absolutely constant temperature without the continuous attention of the experimenter, these experiments at high temperatures could not be extended over periods of several months as in the case of the experiments conducted at ordinary temperatures. The shorter time during which the experiment lasted, however, was in a manner compensated for by increasing the pressure, a higher

[1] C.R., 1867, 603.

[2] "On the Thermal Expansion of Rock at High Temperatures," *Trans. Roy. Soc. of Canada*, 1910.

pressure for a relatively shorter time producing in the case of plastic deformation the same effect as a relatively lower pressure for a longer period. While therefore the temperature, except in the last experiment, was maintained at 450°C., equivalent to a depth of 9 miles below the surface, the pressure was increased until it was equivalent to a depth of 15 miles below the surface, while the time varied from 70 seconds to 70 hours. The results obtained are set forth in the following table.

TABLE II

Table Showing the Effects Produced when Columns of Solenhofen Limestone—Heated to 450°C.—Are Submitted to Pressures Existing at Depths of 10 and 15 Miles within the Earth's Crust

No. of Experiment	Heat	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Equivalent to Pressure Employed	Time	Results
480......	450°C.	64,000	4,500	10 miles	7 hrs.	Holes remain unchanged. No movement of any kind.
374......	450°C.	96,000	6,750	15 miles	70 secs.	Holes become slightly contracted.
362......	450°C.	96,000	6,750	15 miles	7 hrs.	Holes become slightly contracted.
367......	450°C.	96,000	6,750	15 miles	25 hrs.	Holes become slightly contracted.
370......	450°C.	96,000	6,750	15 miles	70 hrs.	Holes become slightly contracted.
371......	450°C.	96,000	6,750	15 miles	70 hrs.	Holes become slightly contracted.
365......	490°C. to 513°C.	96,000	6,750	15 miles	70 hrs.	Transverse hole closed completely.

In this series of experiments it is to be noted that when the rock is submitted to the maximum temperature which can be employed without decomposing it, namely 450°C., which is equivalent to a depth of nine miles below the surface of the earth, no effect is produced if the pressure be raised to that which obtains at a depth of 10 miles. If, however, the pressure is still further increased till it reaches that to which the rock would be exposed

at a depth of 15 miles, a slight diminution in the diameter of the holes is observed, even if this pressure is only maintained for a period of 70 seconds. This movement, however, is not increased even if the rock be maintained at this pressure and temperature for an additional period of 70 hours. In the last experiment, however, when the heat rose for a time to 513°C. the transverse hole, as noted, became completely closed, which may have been connected with a partial disassociation of the Ca CO_3 molecule caused by the high temperature.

GRANITE, WESTERLY, RHODE ISLAND, U.S.A.

A knowledge of the behavior of this rock under deep seated conditions is of especial importance, because it is a typical representative of the great class of plutonic igneous rocks which make up so large a portion of the earth's crust.

This well-known rock is a fresh, fine-grained, massive, pale pink granite, composed essentially of biotite, microcline, orthoclase, and quartz. A detailed description of its microscopic characters as well as the results of a study of its elastic constants are give in Publication No. 46 of the Carnegie Institute of Washington.[1]

The crushing strength of the granite was determined on 2-inch sawed cubes, all the precautions referred to in the case of the Solenhofen limestone being employed to secure accuracy. The results were as follows:

1st cube	= 28,340 lbs. per square inch
2d cube	= 26,410 " " " "
Average	= 27,375 " " " "

It will thus be observed that the rock is not quite so strong as the Solenhofen limestone under the ordinary conditions of a test for crushing strength.

Columns of the granite were prepared, bored, and placed in their enclosing tubes of steel in the manner already described. As in the case of the Solenhofen limestone, a series of experiments

[1] Adams and Coker, *An Investigation into the Elastic Constants of Rocks*, etc., Carnegie Institute of Washington, Washington, 1906.

were first made at the ordinary temperatures. The following table shows the results obtained:

TABLE III

SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF WESTERLY GRANITE—AT THE ORDINARY TEMPERATURE—ARE SUBMITTED TO PRESSURES EXISTING AT SUCCESSIVE DEPTHS WITHIN THE EARTH'S CRUST

No. of Experiment	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Represented by the Pressure	Duration of Pressure	Results
361......	128,000	9,000	20 miles	$2\frac{1}{2}$ mos.	Holes unaltered—No movement.
373......	160,000	11,250	25 miles	$2\frac{1}{2}$ mos.	Holes unaltered—(See Plate II, Fig. a).
356......	199,000	13,990	30.86 miles	15 hrs.	Holes unaltered—No movement—
357......	200,000 (100 tons to sq. inch)	14,060	31 miles	$2\frac{1}{2}$ mos.	Transverse hole unaltered. Vertical hole partly closed at one end by rock powder.
358......	222,500	15,640	35 miles	$2\frac{1}{2}$ mos.	Transverse hole completely filled. Vertical hole largely filled with rock powder—(See Plate II, Fig. b).

It is thus seen that granite at the ordinary temperature, but under the conditions of cubic compression which obtain in the earth, will sustain a load of about 100 tons to the square inch, that is to say, a load rather more than seven times as great as the crushing load of the granite at the surface of the earth under the conditions of the ordinary laboratory test.

In this connection an observation made by P. W. Bridgman is of interest, namely, that under an external hydrostatic pressure amounting to 24,000 atmospheres, or 360,000 pounds to the square inch, continued for 3 hours the cavity of a sealed glass tube did not close or show any sensible change in size or form.[1]

Reference has been made to the nature of the movement observed in the case of the Solenhofen limestone, which seemed to be due in part to flow and in part to fracture.

[1] Quoted by R. A. Daly in his paper on the "Nature of Volcanic Action," *Pro. Am. Acad. of Arts and Sciences*, June, 1911, p. 53.

In the case of the granite the holes when filled are closed by what appear to be minute fragments of granite detached from the walls. In the case of experiment 358, after the removal of the steel the vertical hole as seen from either end was still open and was unaltered in size or shape for a distance of .08 and .24 inch respectively. Beyond that, however, it was blocked up. On removing the steel so as to expose the extremities of the transverse hole, it was found that one end of this hole was completely filled up, no trace of the opening remaining. The locus of the hole was occupied by what seemed to be a part of the rock, finer in grain than the rest and which looks as if it were a perfectly compacted mass of powdered granite. The other extremity of the hole had also been completely closed, although an outline marking its original position could be seen—it was filled with finely granular material clearly crushed granite, imbedded in which were a few relatively larger fragments giving to the whole the appearance of a breccia.

In order to eliminate any error which might be conceived to have been introduced by the pistons expanding under the load and pressing against the sides of the steel tube, thus reducing the amount of pressure exerted on the rock and also to give the rock a better chance to deform by the application of the pressure to the center of the end faces instead of over the entire surface of the faces in question, another experiment was arranged in which the column and its enclosing tube were identical in all respects with those already described but the pistons were .4 inch in diameter while the column had the usual diameter of .5 inch. The proper load to give a pressure of 160,000 lbs. per square inch, equivalent to a depth of 25 miles below the surface, was then applied by this smaller piston to the center of the end faces of the column, for a period of two and a half months, but no change whatever was produced in either the transverse or the vertical hole.

A second series of experiments was then carried out with the Westerly granite in which the factor of heat was introduced.

For the same reason as mentioned in the case of the Solenhofen limestone, the duration of the experiment was necessarily shorter than in the case of the experiments conducted at the ordinary temperature. The results of the experiments are as follows:

TABLE IV

SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF WESTERLY GRANITE—HEATED TO 450°C. AND 550°C.—ARE SUBMITTED TO THE PRESSURE EXISTING AT A DEPTH OF 15 MILES WITHIN THE EARTH'S CRUST

No. of Experiment	Heat	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Equivalent to Pressure Employed	Time	Results
375......	450°C.	96,000	6,750	15 miles	70 secs.	Holes unaltered. No movement.
376......	450°C.	96,000	6,750	15 miles	70 hrs.	Holes unaltered. No movement.
381......	550°C.	96,000	6,750	15 miles	70 hrs.	Holes unaltered. No movement.

As before mentioned, the temperature of 450°C. is that which exists at a depth of 9 miles below the surface, while a temperature of 550°C. is that which is found 11 miles below the surface.

Experiment 381 is one the results of which are of especial interest, for it shows that under the conditions of temperature which exist at a depth of 11 miles below the surface of the earth, open cavities in granite—at least those of relatively small dimensions—*will not close even if the factor of time is allowed for by increasing the pressure over and above that which occurs at a depth of 11 miles by nearly 50 per cent.*

It is further to be noted that this depth of eleven miles (see Fig. 1) is not the extreme depth at which experiment shows that open cavities may exist. They may be present at still greater depths, but the fact that the steel by which the lateral resistance was secured experimentally commences to soften at temperatures of a little over 550°C. makes it impossible to push the experimental investigation by the method employed, to the study of the deportment of the rock at higher temperatures, that is to say, at greater depths.

THE DEPTH TO WHICH MINERAL VEINS AND ALLIED DEPOSITS MAY EXTEND

The present investigation seems to have a rather important bearing on a question of great economic importance, namely, the depth to which mineral veins and replacement deposits may extend in the earth's crust. It must first be noted that the question of

the size of a cavity is one which must be considered in this connection. In the accompanying paper Mr. King has investigated this subject mathematically and shows that in the case of any given rock a pressure might be reached which would be sufficient to crush in larger cavities, but the collapse of the walls instead of leading to the complete closing of the cavity in question would merely result in the formation of a number of smaller spaces, which would remain open permanently or which could only be closed by a greatly increased pressure.

This factor has been eliminated in the present investigation by having the holes in the case of all the experiments identical in size and relatively small.

It is the depth to which these smaller cavities and passages will remain open that is the really important one in connection with the question of the depth to which mineral deposits may extend. For although a great fissure vein may have been developed by the filling of a great fissure, it is considered by some authorities that the crystallographic force of the growing minerals filling the vein has had an important influence in opening up a comparatively narrow fissure, thus making a relatively wide vein in what was originally a comparatively narrow crack. But whether this be so or not, a class of deposits which are much more numerous and more important than "true fissure veins," namely replacements, do not require any originally wide fissures for their development, but are formed by the passage of mineralizing solutions or vapors through narrow cracks or fissures, which serve merely to give such solutions or vapors under high pressures a passage into and through the rock, which they attack and alter and in which they deposit their burden of ores and other valuable minerals by a process of replacement. All, therefore, that is needed for the formation of such deposits are very narrow cavities or fissures to give the mineral bearing solutions access to the rock in which the ores are to be concentrated. Many deposits in shear zones and shattered strips of rock are of this character, as well as other replacement deposits in which the lines of the original fissures are now entirely obliterated.

Whatever, therefore, may be the fate of great yawning chasms if these are formed within the earth's crust at the depths under

consideration in this paper, it is clear that if these are crushed in, smaller cavities will survive even in the crushed mass of rock formed by the collapse of the walls of such a cavity, and will afford ample passage for solutions, vapors, etc., and, therefore, provide the conditions required for the deposition of mineral deposits of the replacement type at least at the great depths in question.

SUMMARY OF CONCLUSIONS

1. The calculations which have been made as to the depth below the earth's surface at which all cavities in the earth's crust would be closed by plastic flow, based on the crushing strength of rocks at the surface of the earth, are erroneous.

2. At ordinary temperatures but under the conditions of hydrostatic pressure or cubic compression which exist within the earth's crust, granite will sustain a load of nearly 100 tons to the square inch, that is to say, a load rather more than seven times as great as that which will crush it at the surface of the earth under the conditions of the usual laboratory test.

3. Under the conditions of pressure and temperature which are believed to obtain within the earth's crust, empty cavities may exist in granite to a depth of at least 11 miles. These may extend to still greater depths, and if filled with water, gas or vapor, will certainly do so, owing to the pressure exerted by such fluids or gases upon the inner surfaces of such cavities or fissures.

4. Since the existence of open spaces through which aqueous solutions, vapors, or gases can traverse a rock is a factor in the development of mineral veins and replacement deposits, such veins and deposits may be formed within the earth's crust to a depth of at least 11 miles below the surface. That is to say, they may extend to a much greater depth than it is possible to follow them by any method of mining now employed.

DESCRIPTION OF PLATES

PLATE I

FIG. *a.*—Shows a column of Solenhofen limestone (Exp. 359) which has been submitted to a pressure equivalent to a depth of 15 miles within the earth's crust for $2\frac{1}{2}$ months. The steel tube has been partially removed so as

to expose the transverse hole. This latter is seen to have been unaffected by the pressure.

FIG. *b*.—This is a column of Solenhofen limestone (Exp. 520) which has been submitted to a pressure of 100 tons to the square inch equivalent to a depth of 31 miles below the surface of the earth, for half an hour. The steel which enclosed it has been completely removed. There has been a slight movement of the nature of plastic flow developed in the rock, owing to which the transverse hole originally circular in outline has been flattened so that it now presents a lenticular cross-section.

FIG. *c*.—This is experiment 383. The column of Solenhofen limestone was submitted to a pressure equivalent to a depth of 40 miles below the earth's surface—for seven hours. The steel tube was then removed but in the process the column broke in two along the line of the transverse hole (seen at the top of the photograph) and also split vertically along the line of the vertical hole. A vertical section of one-half of the column is shown. For about one-half its length along the central part of the column the vertical hole remains unaltered but from this unaltered part, and with increasing intensity toward either end of the column minute crescentic cracks form on the wall of the hole, along which cracks little fragments of the rock separate and fill the hole more or less completely.

FIG. *d*.—This is a reproduction of a photograph of a thin section cut vertically through the column of Solenhofen limestone of experiment 360. It shows the walls of the vertical hole with the minute cracks referred to in Fig. *c*.

PLATE II

FIG. *a*.—Shows a column of Westerly granite (Exp. 373) which has been submitted to a pressure equivalent to a depth of 25 miles below the surface of the earth for $2\frac{1}{2}$ months. The steel tube has been partially removed exposing the transverse hole, which has been absolutely unaffected by the pressure.

FIG. *b*.—Shows a column of Westerly granite (Exp. 358) which has been exposed to a pressure equivalent to a depth of 35 miles below the surface of the earth, for $2\frac{1}{2}$ months. Under this pressure, as seen, the transverse hole has been filled in. The irregular dark spot, marking the original position of the hole, is caused by the breaking away of a little granite when the steel tube was being removed.

FIG. *c*.—This shows the cracks referred to in the description of Plate I, Figs. *c* and *d;* but they are especially pronounced because in this case (Exp. 384) the steel tube was thinned away about the middle of the column of Solenhofen limestone, permitting the latter to bulge out laterally, thus giving a greater freedom of movement. It was submitted to a pressure of 204,000 lbs. per square inch, equivalent to a depth of rather over 31 miles below the surface of the earth.

ON THE LIMITING STRENGTH OF ROCKS UNDER CONDITIONS OF STRESS EXISTING IN THE EARTH'S INTERIOR

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§ I. INTRODUCTION

One of the most important problems in geophysics is to obtain a knowledge of the limiting strength of the material forming the solid core of the earth as well as that of the principal rocks forming its crust. According to the modern theory of elasticity the tendency of a solid to rupture is measured by the maximum difference of the greatest and least principal stresses. This criterion first due to Tresca and followed by Sir G. H. Darwin[1] has been found by J. J. Guest[2] to give the best agreement with observed results from experiments on metal tubes subjected to various systems of combined stress. Coulomb's suggestion that the greatest shear produced in a material is a measure of its tendency to rupture leads to a result substantially the same as that given by the hypothesis of maximum stress-difference. This follows from the theorem[3] that the shearing stress at any point is greatest on a plane whose normal lies in the plane of the axes of the algebraically greatest and algebraically least stress and bisects the angle between them, its value being half the algebraic difference between these stress-intensities. The family of surfaces whose tangent planes satisfy the above condition determines the surfaces along which flaws will develop or the material commence to rupture. These surfaces are are called *surfaces of maximum shear.*

The difficulty in the way of the practical application of these criteria lies especially in the determination of the numerical values of the limiting stress-difference for different materials. For the

[1] Darwin, "On the Stresses Produced in the Interior of the Earth by the Weight of Continents and Mountains," *Phil. Trans. Roy. Soc.*, CLXXIII (1882).

[2] Guest, *Phil. Mag.* (Ser. 5), XLVIII (1900).

[3] Minchin, *Statics*, 4th ed., 1889, II, 425.

purposes of ordinary engineering practice, a cube of the material is put into a testing-machine and the stress required to crush the cube is measured. The value of this stress per unit area gives the value of the limiting stress-difference for the material *as long as the boundary conditions are similar to those existing during the test.* Although this condition generally holds in engineering construction work and the criterion is valid, this may by no means be the case when the boundary conditions are very different from those existing in the test, as for instance in the case of rupture in the neighborhood of a cavity or in the case of rupture due to stress-difference deep down in the earth's crust. It has been customary up to the present to employ the crushing test criterion in applications to stresses in the earth's interior.[1] A mathematical analysis of the experiments of Dr. Adams,[2] described in the accompanying paper, throws a great deal of light on the question and can be made to give valuable data on the limiting strength of rocks under conditions of extreme pressure.

It will appear that the crushing test criterion of limiting stress-difference (e.g., 27,000 lbs. per sq. in. for a cubical specimen of Westerly granite of two inches side) is much too low when conditions of stress approach those existing in the earth's interior.

For the purposes of geodynamics, however, "we require to know what is the limiting stress-difference under which a material takes a permanent set or begins to flow rather than the stress-difference under which it breaks; for if the materials of the earth were to begin to flow, the continents would sink down and the sea-bottoms rise up."[3]

A mathematical analysis of tests described in § 4 afford a valuable means of obtaining information on this question.

§ 2. CONDITIONS OF TEST

The tests described by Dr. Adams on the compression of cylindrical rock specimens containing cylindrical cavities and inclosed

[1] Darwin, *loc. cit.*

[2] Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow," see this journal, p. 97.

[3] Darwin, *loc. cit.*

in heavy nickel-steel jackets lend themselves especially well to a determination of stress-differences according to the elastic solid theory. An indeterminate condition which might vitiate the application of analysis to the problem is the state of initial stress brought about by shrinking the nickel-steel jacket over the rock specimen. Since the ends of the specimen are free during this process it is probable that the rock will adapt itself to a state of small initial stress by slight displacements in the direction of the axis. This will especially be the case if some time is allowed to elapse before the test is carried out. Care was taken to make this stress as small as possible under the circumstances; see p. 105.

One of the most serious objections to the application of the theory of elasticity to the determination of conditions of rupture lies in the fact that in most tests the conditions of small strains upon which the theory is based are violated long before rupture takes place. Under the conditions just described the strains remain small in consequence of the very slight yielding of the nickel-steel jacket. It is well known that the elastic constants are only determinate so long as the strains are small and that when the material is stressed beyond a certain limit the rigidity and compressibility take quite different values, so that in most cases the values of the stresses just before rupture cannot be calculated from the conditions of the test. In the present instance, however, by measuring the lateral dilatation of the nickel-steel jacket during a test in the manner described in §4, it is possible to determine how the elastic constants of the rock change in value with stress. In this way it is legitimate to make use of the equations of the elastic solid theory, provided we employ *instantaneous* values of the constants for the specimen and as long as the stresses in the nickel steel do not exceed the limiting stress for that material.

§ 3. DETERMINATION OF STRESSES IN ROCK CYLINDER UNDER TEST

If we consider the state of stress in the rock specimen and in the nickel-steel jacket as one of plane stress, the problem may be solved without an undue degree of complication. The measurements given in the next section of the lateral dilatation of the nickel-steel jacket when the rock specimen is under pressure show

a considerable bulge of the equatorial diameter, showing that the problem is not strictly one of plane stress. The complete solution of the problem would be of the nature of a similar one considered by Filon[1] in which the state of stress is determined for a cylinder pressed between planes which are in contact with its ends. For the purposes of the present paper, however, we shall deal with the problem as one of plane stress and neglect surface tractions, over the boundary of the cylindrical specimen due to relative displacements of the rock surface and the steel jacket when under pressure. The results will represent to a first approximation the state of stress existing in the rock specimen. From the general solution of the problem given by Love[2] it is an easy matter to calculate the stress-differences at any point of the specimen. According to the usual notation we denote by $\widehat{rr}$, $\widehat{\theta\theta}$, and $\widehat{zz}$ the radial, transverse, and axial stresses respectively: for a case of plane stress there are also the principal stresses. We denote the differences of the principal stresses by the notation

(i) $\widehat{rr}-\widehat{zz}$ (ii) $\widehat{rr}-\widehat{\theta\theta}$ (iii) $\widehat{\theta\theta}-\widehat{zz}$

From the theorem cited in § 1 it is seen that each of the stress-differences (i), (ii), (iii) is associated with a family of surfaces of maximum shear along which the material will crack or flow.

(i) The surfaces of maximum principal shear due to the stress-differences $(\widehat{rr}-\widehat{zz})$ consist of two systems of cones of semi-vertical angle 45° and cutting each other orthogonally. One such system may be imagined to consist of a pile of glass funnels fitting into one another.

(ii) The surfaces of shear due to the stress-differences $(\widehat{rr}-\widehat{\theta\theta})$ consist of two systems of mutually orthogonal cylindrical surfaces whose traces on a plane perpendicular to the axis of the cylinder are equiangular spirals cutting the radii at angles of 45°.

(iii) The stress-differences $(\widehat{\theta\theta}-\widehat{zz})$ give rise to two families of helicoidal surfaces of pitch 45° and intersecting orthogonally. The traces of these surfaces on the surface of the cylinder give rise to helices well known as Luder's lines.

[1] L. N. G. Filon, "On the Elastic Equilibrium of Circular Cylinders under Certain Practical Systems of Load," *Phil. Trans. Roy. Soc.*, CXCVIII A, 1902, 182.

[2] Love, *Elasticity*, 2d ed., 140.

The systems of surfaces of shear corresponding to each of the above cases are shown as (i), (ii), and (iii) in Fig. 1. The cracks developed by failure in each of the above ways as they would appear on the cylindrical surface, over a cross-section perpendicular to the axis and over a section through the axis are represented by the diagrams (i), (ii), and (iii).

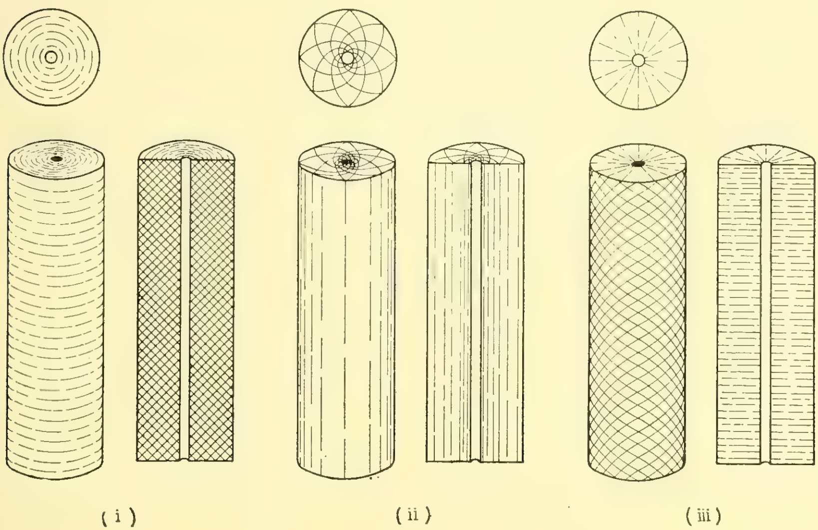

FIG. 1

The surfaces of shear developed in a cylinder under test will depend on which of the stress-differences is a maximum, a condition determined by the elastic constants of the rock and also by the nature of the nickel-steel boundary. As soon as this maximum stress-difference has attained a limiting value characteristic of the material, and determined to some extent by the boundary conditions the corresponding families of surfaces of shear will make their appearance.

Considering first the stresses in the rock specimen, the radial displacement U satisfies the equation

$$\frac{\partial}{\partial r}\left(\frac{\partial U}{\partial r}+\frac{U}{r}\right)=0,$$

of which the complete primitive is

$$U=Ar+\frac{B}{r}, \tag{1}$$

A and B being constants to be determined from the specified boundary conditions. Longitudinal stress superimposed upon the radial stresses can be taken into account by taking the displacement w in the direction of the axis to be $w=ez$, e being a constant representing a uniform longitudinal extension.

If we denote by $\widehat{rr}$ the stress-component along the radius r, by $\widehat{\theta\theta}$ the component at right angles to r and by $\widehat{zz}$ that along the axis, we find from the stress-equations of equilibrium,

$$\left.\begin{aligned}
\widehat{rr}&=(\lambda+2\mu)\frac{\partial U}{\partial r}+\lambda\frac{U}{r}+\lambda\frac{\partial w}{\partial z}\\
\widehat{\theta\theta}&=(\lambda+2\mu)\frac{U}{r}+\lambda\frac{\partial U}{\partial r}+\lambda\frac{\partial w}{\partial z}\\
\widehat{zz}&=(\lambda+2\mu)\frac{\partial w}{\partial z}+\lambda\left(\frac{U}{r}+\frac{\partial U}{\partial r}\right)
\end{aligned}\right\} \tag{2}$$

According to Lamé's notation μ is the modulus of rigidity and λ one of the moduli of elasticity such that $\kappa=(\lambda+\frac{2}{3}\mu)$ is the modulus of compression. Poisson's ratio, σ, is denoted by $\sigma=\dfrac{\lambda}{2(\lambda+\mu)}$.

In terms of A and B of equation (1) we have for the principal stresses and the hydrostatic pressure p

$$\left.\begin{aligned}
\widehat{rr}&=2(\lambda+\mu)A-\frac{2\mu}{r^2}B+\lambda e\\
\widehat{\theta\theta}&=2(\lambda+\mu)A+\frac{2\mu}{r^2}B+\lambda e\\
\widehat{zz}&=2\lambda A+(\lambda+2\mu)e\\
p&=-\tfrac{1}{3}(\widehat{rr}+\widehat{\theta\theta}+\widehat{zz})=-\kappa(A+e)
\end{aligned}\right\} \tag{3}$$

If accented letters refer to corresponding quantities in the coaxial nickel-steel jacket, we have for the principal stresses a set of equations analogous to (1) and (3),

$$\left.\begin{aligned} U' &= A'r' + B'/r' \\ \widehat{rr}' &= 2(\lambda'+\mu')A' - \frac{2\mu'}{r'^2}B' + \lambda' e' \\ \widehat{\theta\theta}' &= 2(\lambda'+\mu')A' + \frac{2\mu'}{r'^2}B' + \lambda' e' \\ \widehat{zz}' &= 2\lambda' A' + (\lambda'+2\mu')e' \end{aligned}\right\} \quad (4)$$

Let a be the radius of the cylindrical cavity in the rock specimen, b the radius of the specimen, and c the radius of the nickel-steel jacket. The boundary conditions give six equations to determine the constants A, B, e, A', B', e'.

At $r=a$, $\widehat{rr}=0$, giving

$$2(\lambda+\mu)A - 2\mu B/a^2 + \lambda e = 0 \quad (5)$$

At $r=r'=b$, $\widehat{rr}=\widehat{rr}'$, giving

$$2(\lambda+\mu)A - 2\mu B/b^2 + \lambda e = 2(\lambda'+\mu')A' - 2\mu' B'/b^2 + \lambda' e' \quad (6)$$

At $r=r'=b$, $U=U'$, giving

$$Ab + B/b = A'b + B'/b \quad (7)$$

At $r'=c$, $\widehat{rr}=0$, giving

$$2(\lambda'+\mu')A' - 2\mu' B'/c^2 + \lambda' e' = 0 \quad (8)$$

In addition to these we have in the rock specimen, $\widehat{zz}=-P$, where P is the pressure per unit area applied to the end of the test cylinder; this condition gives

$$2\lambda A + (\lambda+2\mu)e = -P \quad (9)$$

Also since the nickel-steel jacket is free from longitudinal stress,

$$\widehat{zz}' = 0 \text{ or } 2\lambda' A' + (\lambda'+2\mu')e' = 0 \quad (10)$$

We denote by β the quantity,

$$\beta = \frac{1+\sigma}{1-\sigma} \cdot \frac{\mu}{\mu'} \left\{ \left(1 + \frac{1-\sigma'}{1+\sigma'} \frac{b^2}{c^2}\right) \frac{1-a^2/b^2}{1-b^2/c^2} + \frac{\mu'}{\mu} a^2/b^2 \right\}. \quad (11)$$

We then find from the six equations (5) to (10),

$$\left.\begin{aligned} \frac{B}{a^2} &= -\frac{P}{2\mu} \cdot \frac{\sigma}{1-\sigma} \frac{1}{1+\beta} \\ \text{and} \quad e - A &= -\frac{P}{\lambda+2\mu} \left\{ 1 + \frac{\sigma}{1-2\sigma} \frac{\beta}{1+\beta} \right\} \end{aligned}\right\} \quad (12)$$

The principal stress-differences in the rock specimen are from (3)

$$\left.\begin{aligned}
&\text{(i)}\ \widehat{rr}-\widehat{zz}=-2\mu(e-A+B/r^2)\\
&\qquad\qquad=\frac{\sigma}{1-\sigma}P\left\{\frac{1-2\sigma}{\sigma}+\frac{\beta}{1+\beta}+\frac{1}{1+\beta}\frac{a^2}{r^2}\right\}\\
&\text{(ii)}\ \widehat{rr}-\widehat{\theta\theta}=-4\mu B/r^2 \qquad =\frac{\sigma}{1-\sigma}P\left\{\frac{2}{1+\beta}\frac{a^2}{r^2}\right\}\\
&\text{(iii)}\ \widehat{\theta\theta}-\widehat{zz}=-2\mu(e-A-B/r^2)\\
&\qquad\qquad=\frac{\sigma}{1-\sigma}P\left\{\frac{1-2\sigma}{\sigma}+\frac{\beta}{1+\beta}-\frac{1}{1+\beta}\frac{a^2}{r^2}\right\}
\end{aligned}\right\} \tag{13}$$

The radial displacement U at the outer surface of the rock specimen is given by

$$\frac{U}{b}=\frac{P}{2\mu}\frac{\sigma}{1+\sigma}\frac{\beta-\dfrac{a^2}{b^2}\dfrac{1+\sigma}{1-\sigma}}{1+\beta} \tag{14}$$

and the longitudinal extension per unit length is given by

$$e=-\frac{P}{2\mu}\frac{1}{1+\sigma}\frac{\beta+\dfrac{(1+\sigma)(1-2\sigma)}{1-\sigma}}{1+\beta} \tag{15}$$

The radial displacement U' at the outer surface of the nickel-steel jacket is given by

$$\frac{U'}{c}=\frac{P}{\mu'}\frac{b^2}{c^2}\frac{1-a^2/b^2}{1-b^2/c^2}\frac{\sigma}{(1-\sigma)(1+\sigma')(1+\beta)} \tag{16}$$

and the longitudinal extension per unit length is given by

$$e=-\sigma'\frac{U'}{c} \tag{17}$$

§ 4. DISCUSSION OF EXPERIMENTAL RESULTS

In order to obtain a numerical verification of the distribution of stress in the rock specimens, measurements of the lateral bulging of the nickel-steel jacket were made by means of a very sensitive Ewing extensometer for a series of increasing loads. The results were obtained for a specimen of Solenhofen limestone in which an axial and transverse cavity had been drilled, and the experiments carried out in the Engineering Testing Laboratory of McGill University.

TABLE I

TABLE GIVING RADIAL DISPLACEMENT OF NICKEL-STEEL JACKET CONTAINING A SPECIMEN OF SOLENHOFEN LIMESTONE UNDER VARYING LOADS

P Pounds per Square Inch	$\frac{U'}{c}\times 10^{-6}$ Radial Displacement at Center	$\frac{U'}{c}\times 10^{-6}$ Radial Displacement over End	Remarks
5,100	0	0	Diameter of nickel-steel jacket 2.5 in., $c=1.25$;
25,500	16	0	length of nickel-steel jacket 3.25 in.
51,000	34	4	Diameter of rock specimen before loading .5005 in.,
76,500	50	10	$b=.2502$ in.; length of rock specimen before
102,000	76	18	loading 1.5725 in.
127,000	106	24	*Load removed*, diam. of specimen at ends .5052 in.;
153,000	154	38	diam. of specimen at equator .5030 in.; length
175,000	210	46	1.5437 in.
200,000	326	66	Diameter of cylindrical cavities .050 inch.
5,100	124	38	*Load removed*, vertical cavity filled with rock powder,
1,000	124	38	horizontal cavity distorted.
1,000	116	37.5	Longitudinal compression of jacket between 2 in. centers .00003 in., per load of 200,000 pounds. Last reading taken 45 hours after preceding measurement.

The nickel-steel jacket used contains about 5 per cent of nickel; the elastic constants of nickel-steel containing $5\frac{1}{2}$ per cent of nickel are taken to be $\mu'=10.8\times 10^6$ pounds per sq. in., $\sigma'=.327$,[1] values not very different from these ordinarily given for steel.

The constants for the Solenhofen limestone of which the rock specimen is made have not been determined; the rock in question resembles in its structure and properties black Belgian marble for which the elastic constants are $\mu=4.33\times 10^6$ pounds per sq. in., $\sigma=.278$.[2]

In calculating the value of β from (11) we may neglect a^2/b^2 and since $b^2/c^2=.04$ we find $\beta=.77$. Equation (16) then gives

$$\frac{U'}{c}=\frac{P(\text{pound per sq. in.})}{1.57\times 10^9} \tag{18}$$

Taking P=200,000 pounds per sq. in. we have $U'/c=127\times 10^{-6}$.

The observed radial strain over the center of the specimen is considerably greater than this. We may attribute the difference to a diminution of rigidity. Taking as an extreme case $a=0$ and $\mu=0$,

[1] Mercadier, *Comptes Rendus*, 113, 1891.

[2] Adams and Coker, *Elastic Constants of Rocks*, Carnegie Institution, 1906.

$\sigma=\frac{1}{2}$ (incompressible fluid in the nickel-steel jacket), we have $\beta=0$. Then

$$\left(\frac{U'}{c}\right)_{\mu=0}=\frac{P(\text{pounds per sq. in.})}{.345\times 10^9}, \tag{19}$$

which gives for $P=200{,}000$ pounds,

$$\left(\frac{U'}{c}\right)_{\mu=0}=578\times 10^{-6}$$

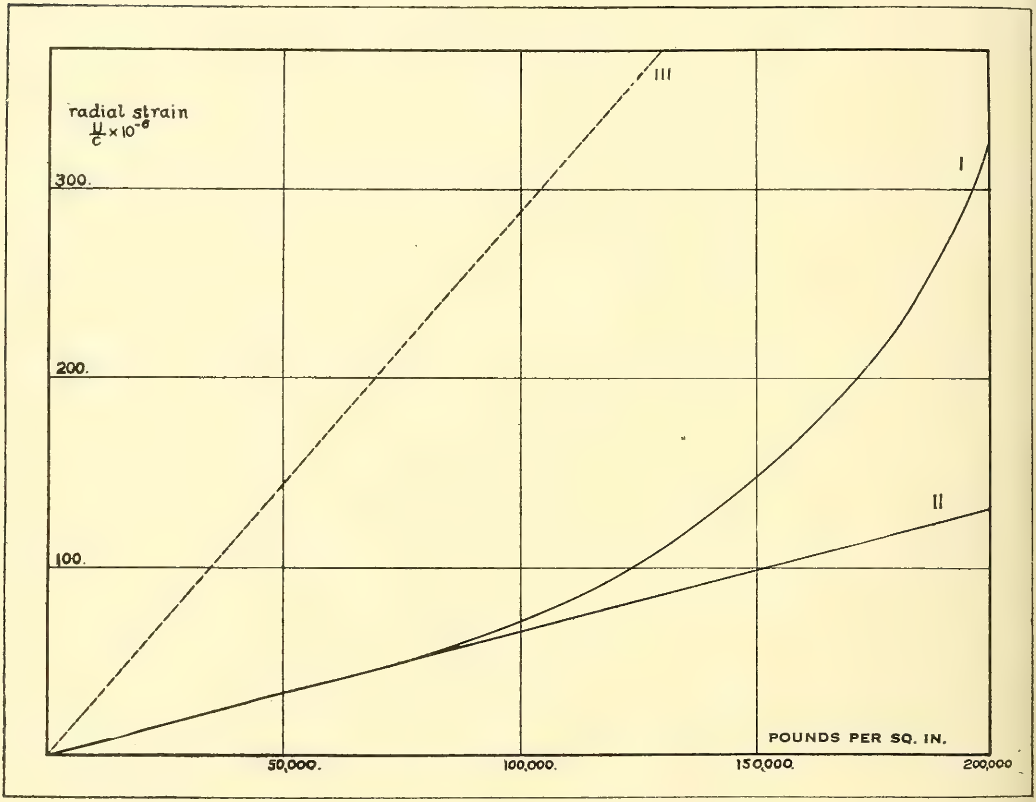

FIG. 2.—Showing relation between radial strain and load for a nickel-steel jacket containing a specimen of Solenhofen limestone under test.

Curve I shows the observed radial strain over the center of the specimen.

Curve II shows the radial strain calculated according to the elastic solid theory for rigidity $\mu=4.33\times 10^6$ pound per sq. in. and Poisson's ratio $\sigma=.278$.

Curve III shows the calculated relation between strain and stress for a specimen of zero rigidity.

The results given in Table I are shown graphically in Fig. 2, where the radial strains are plotted on a load base. Equation (16) shows that if the rock specimen had behaved throughout as a perfectly elastic solid, U'/c should be proportional to the load, and the curve connecting load and strain should be a straight line. Even taking into account the equatorial bulge of the nickel-steel jacket the proportionality of strain to stress should be exact on the elastic solid theory.[1] We may interpret the results just obtained to a gradual change in the value of the elastic constants which may be regarded as continuous functions of the stress-differences; in fact, if the departure of Curve I of Fig. 2 from a straight line be attributed to a change in the modulus of rigidity, the variation of the latter with stress-difference might be deduced from an analysis of the curve. The theoretical curve for the radial strain over the center of the specimen agrees well with that observed until a load of 80,000 pounds per sq. in. is reached. A curve for the displacement that would be given if the specimen possessed zero rigidity and a Poisson's ratio of $\frac{1}{2}$ is also shown in the diagram. The departure of the observed curve from that obtained on the hypothesis of perfect elasticity shows that the rigidity modulus diminishes under load and that Poisson's ratio increases toward the limit $\frac{1}{2}$. The observations also indicate that when the load is removed the specimen has received a permanent set with a tendency to recovery with time, showing an indication of elastico-viscous properties.[2] The elastic moduli are also permanently changed; a curious fact explained by this means is that the specimen after having been tested shows a smaller diameter across the center than across the ends, whereas the radial displacement was greatest at that point. Since the displacements were greatest in the central part of the specimen it is reasonable to suppose that the rigidity is permanently altered to a lesser value than in the ends. The result is that when the load is removed the lateral pressure exerted by the nickel-steel jacket is able to produce a greater displacement at the center of the specimen than at the ends, so that a slight waist is produced in the rock cylinder.

[1] Cf. Filon, *loc. cit.*

[2] G. H. Darwin, "On the Bodily Tides of Viscous and Semi-elastic Spheroids," *Phil. Trans. Roy. Soc.*, CLXX, 17.

§ 5. ON THE CONDITIONS OF RUPTURE IN CYCLINDRICAL ROCK SPECIMENS UNDER CONDITIONS OF EXTREME PRESSURE

An examination of equations (13) shows that the stress-differences (i) and (iii) take their maximum values at $r=a$, and that (iii) takes its maximum value at $r=b$. We thus obtain for the maximum values of the stress-differences

$$\left.\begin{aligned} &\text{(i)}\ \widehat{rr}-\widehat{zz}=P \\ &\text{(ii)}\ \widehat{rr}-\widehat{\theta\theta}=\frac{\sigma}{1-\sigma}\cdot\frac{2}{1+\beta}\cdot P \\ &\text{(iii)}\ \widehat{\theta\theta}-\widehat{zz}=P\left\{1-\frac{\sigma}{1-\sigma}\cdot\frac{1}{1+\beta}\left(1+\frac{a^2}{b^2}\right)\right\} \end{aligned}\right\} \quad (20)$$

We note that (i) > (ii) provided $\beta>\frac{3\sigma-1}{1-\sigma}$. Also (i) > (iii) in all cases except when $\beta=\infty$ $(b=c)$ in which case (i) = (iii).

Thus if

$$\beta>\frac{3\sigma-1}{1-\sigma}\quad \text{(i)} > \text{(ii) and (i)} > \text{(iii)} \quad (21)$$

so that the specimens will develop the system of surfaces of shear shown in (i) Fig. 1.

$$\text{If } \beta<\frac{3\sigma-1}{1-\sigma} \text{ we have (ii)} > \text{(i)} > \text{(iii)} \quad (22)$$

In this case the system of surfaces of shear described in (ii), Fig. 1, will make their appearance.

In applying the criterion

$$\beta\gtrless\frac{3\sigma-1}{1-\sigma} \quad (23)$$

it is necessary to employ instantaneous values of the elastic constants, since from the previous section these are seen to depend on the load. If from (11) we write approximately $\beta=\frac{\mu}{\mu'}\frac{1+\sigma}{1-\sigma}$ corresponding to $c=\infty$, and $a=0$, the criterion (23) may be written

$$\mu/\mu'\gtrless\frac{3\sigma-1}{1+\sigma}.$$

As long as $\sigma<\frac{1}{3}$ the first of these criteria given in (21) is always satisfied. We have seen, however, that the rigidity μ tends to

diminish with load, while σ tends to the value $\frac{1}{2}$. Under these conditions it is quite possible that the condition $\beta<\frac{3\sigma-1}{1-\sigma}$ given in (22) may be satisfied before the specimen actually begins to rupture in the neighborhood of the cylindrical cavity. The breakdown of a rock specimen under these conditions would be characterized by a tendency to split across a plane through the axis: over a cross-section a system of spiral cracks cutting the cylindrical cavity at an angle would make their appearance and long splinters parallel to the axis would break off from the interior of the cylindrical cavity. Actual cases of fractures of this kind are described by Dr. Adams in the preceding paper.[1] We note that for a solid cylinder ($a=0$) the stress-difference (i) = (iii), so that the conditions for the appearance of the surfaces of shear (i) and (iii) are identical. System (iii) is characterized by the appearance of Luder's lines over the surface of the specimen; these in fact are often observed.

§ 6. ON THE LIMITING STRESS-DIFFERENCE IN THE NEIGHBORHOOD OF A SMALL CYLINDRICAL CAVITY

The preceding analysis may be applied to a determination of the limiting stress-difference S in the neighborhood of the small cylindrical cavities in the specimens of Westerly (Rhode Island) granite tested by Dr. Adams and described in the preceding paper. This granite gave a crushing strength of 27,370 pounds per sq. in. for a two-inch cube. If we note that for this granite $\sigma=.219$,[2] the condition $\beta>\frac{3\sigma-1}{1-\sigma}$ is satisfied and the greatest stress-difference in the specimen is P, so that $S=P$. Experiments 373 and 357 described in Dr. Adams' paper (p. 113) enable a limit to be assigned to the value of S. In experiment 373 a pressure P of 160,000 pounds per sq. in. applied during 75 days produced no change in the diameter of the cylindrical cavity, indicating that no flow or permanent set had taken place. In the case of a similar specimen tested under a pressure P of 200,000 pounds for the same length of time, it was found that the vertical cavity was partly closed up by

[1] Adams, p. 109 of this journal, Plate I, figs. *c* and *d;* Plate II, fig. *c*.

[2] Adams and Coker, *loc. cit.*

rock powder. We are therefore able to assert that for a state of stress at ordinary temperature and lasting for 75 days, S lies between the limits of 160,000 and 200,000 pounds per sq. in., i.e.,

$$160{,}000 < S < 200{,}000 \text{ pounds per sq. in.} \tag{24}$$

Even at a temperature of 550° C. experiment 381 (p. 115) shows that S is greater than 96,000 pounds per sq. in.

We cannot, however, safely assert that flow or rupture would not take place for a stress-difference less than S if the boundary conditions were very different from these already described at the surface of a cylindrical cavity. In order to settle this point experiments of the type described in § 4 would be required. The value given in (24) for S is very much greater than the limiting stress-difference of 27,000 pounds per sq. in. obtained by means of the usual crushing test. Since this granite is typical of the great mass of igneous rocks which make up the earth's crust, it follows that in geophysical problems which involve a knowledge of limiting stress-difference in the earth's crust, a value considerably higher than that usually employed must be taken.

§ 7. ON THE EXISTENCE OF CAVITIES IN MEDIA UNDER STRESS

(i) *State of Stress in the Neighborhood of Cavities in Elastic Media under Shear*

It can be shown that in the neighborhood of both a spherical and a cylindrical cavity, the shear can be nearly equal to twice the shear at a distance.[1] We see therefore that the medium near a cavity will collapse if the stress-difference at a distance exceeds half the limiting stress-difference of the rock material. If the cavity be small this limiting stress-difference may be taken to be the value of S given in equation (24).

(ii) *State of Stress in the Neighborhood of a Spherical Cavity in a Medium under Pressure*

If p be the hydrostatic pressure in the medium it can easily be shown from the solution given by Love[2] for a spherical shell under

[1] Love, *Elasticity*, 2d ed., 245. See also a paper by Larmor, *Phil. Mag.* (Ser. 5), XXXIII, 1892, p. 77.

[2] Love, *op. cit.*, 139.

external pressure that the maximum stress-difference in the neighborhood of the cavity is $\frac{3}{2}p$. This result is independent of the elastic constants and of the radius of the cavity. If then the pressure in the medium exceeds $\frac{2}{3}$ the limiting stress-difference of the rock, the cavity will break down. The value of S given in (24) for the limiting stress-differences may be employed provided the radius of the cavity be small.

(*iii*) *On the Stability of a Spherical Cavity in a Medium under Pressure*

That the result quoted in (ii) should be independent of the radius of the cavity seems contrary to experience. The explanation of this anomaly lies in the fact that the question turns on an examination of *stability* rather than on a purely *static* consideration of stress. A problem of a similar kind is that of the collapse of a thin-walled cylinder (e.g. a boiler flue) under external pressure.[1] The result shows that for a cylindrical shell of infinite length collapse will not occur as long as the pressure does not exceed

$$p = \frac{4\mu}{1-\sigma}\left(\frac{t}{a}\right)^3 \qquad (25)$$

where μ and σ denote the rigidity modulus and Poisson's ratio for the material and t/a is the ratio of the thickness to the diameter. The vibrations in the neighborhood of a spherical cavity in an infinite medium under hydrostatic pressure do not appear to have been explicitly worked out; the problem would correspond to the external solution of the problem of the vibrations of a solid elastic sphere.[2] In so far as the stability depends on the radial vibrations of the cavity, a solution could easily be adapted from Poisson's solution for the case of a solid elastic sphere.[3] The result of an investigation on stability would give a result analogous to (25) for a cylindrical shell. When the pressure p is specified the condition of stability will lead to a limiting radius which will be determined by the elastic constants of the medium. A cavity having a greater

[1] Love, *op. cit.*, 530.

[2] Cf. Love, "Gravitational Stability of the Earth," *Phil. Trans.*, 207 A, 1908.

[3] Poisson, "Mémoire sur l'équilibre et le mouvement des corps élastiques," *Mém. Paris Acad.*, t. 8, 1829.

radius than this limiting radius will be unstable and collapse in such a way as to form a number of smaller cavities each of which might be stable.

§ 8. NOTE ON CONDITIONS OF STRESS IN THE EARTH'S CRUST

The determination of conditions of stress existing in the earth's crust constitutes one of the most difficult problems of geodynamics and one on which many recent investigations have been published. If the earth is considered as a perfect sphere in which the density is a function of the radius only, the problem can be solved without difficulty in terms of the elastic solid theory.[1] The application of these results throughout the interior of the earth is not legitimate because an infinite number of laws of density can be formulated to represent the known distribution of mass throughout the earth. Near the surface considerations of surface inequalities vitiate the result. In this connection Love states,[2] "Apart from the difficulty concerning the initial stress in a gravitating body of the size of the earth, a difficulty which we seem unable to avoid without treating the material as incompressible, there is another difficulty in the application of such an analysis to problems concerning compressible gravitating bodies. In the analysis we take account of the attraction of the inequality at the surface, but we neglect the inequalities of the internal attraction which arise from the changes of density in the interior; yet these inequalities of attraction are of the same order of magnitude as the attraction of the surface inequality."

In a recent work Love[3] has attacked the problem of isostatic support of continents and mountains. "The problem admits of an infinite number of solutions even if the distribution of the mass is known. . . . . The problem must remain indeterminate, and all we can do is to obtain explicitly one or more of the infinitely

[1] Lamé solves the problem for an isotropic elastic sphere under its own gravitation (Love, *Elasticity*, 2d ed., 140); the result can only be reconciled with fact by the assumption of incompressibility or by taking into account a state of initial stress. L. M. Hoskins in a paper "Flow and Fracture of Rocks as Related to Structure" (*U.S. Geological Survey*, 1894–95, Part I, 854), solves the problem throughout a compressible concentric crust of uniform density and small thickness; no account is taken, however, of surface inequalities or of considerations of isostasy.

[2] Love, *Elasticity*, 2d ed., 253.

[3] Love, *Some Problems of Geodynamics* (*Adams Prize Essay*, 1911), chaps. ii and iii, p. 12.

numerous solutions. One solution of the problem was obtained by Sir G. Darwin[1] by assuming that the stress is connected with a displacement by the same equations as hold in the ordinary theory of an elastic *incompressible* solid, ... "

The theoretical developments turn on the calculation of stress-differences corresponding to surface inequalities representing continental blocks and mountains. Expressions for the hydrostatic pressure at any depth are not explicitly worked out although it would be possible to calculate from the analysis given the pressure at any depth due to those harmonic inequalities which Love has shown can be made to represent the existing distribution of land and water and the general form of continental blocks. For most purposes it is sufficient to calculate the pressure at any depth as that due to the weight of the corresponding column of rock: this formula gives a value of greater relative accuracy the greater the depth at which the pressure is calculated.

§ 9. DEPTH AT WHICH CAVITIES CAN EXIST

(*i*) *Collapse Due to Stress-Differences in the Earth's Crust*

Love[2] shows that on the isostatic theory the maximum stress-difference due to a harmonic inequality of the third order representing a continental block of maximum elevation 2 kms. is approximately the weight of a column of rock equal to 0.0208 of this greatest height, i.e., about 0.0114 of a metric tonne per sq. cm. (162 pounds per sq. in.). This value is greater than that brought about by inequalities of the first and second order. The stress-difference is also worked out for a parallel series of mountain ranges 400 kilometers apart and having a height of 4 kms. from crest to valley-bottom; it is shown that the greatest value of the stress-difference is about .26 metric tonnes per sq. cm. (3,700 pounds per sq. in.). In both cases the stress-difference is very much less than $\frac{1}{2}S$ so that no state of stress-difference due to weights of continents or mountains is intense enough to cause the material of the earth's crust to rupture in the neighborhood of a small cavity.

[1] Darwin, "On the Stresses Caused in the Interior of the Earth by the Weight of Continents and Mountains," *Phil. Trans. Roy. Soc.*, CLXXIII (1882).

[2] Love, *op. cit.*, 36; also 47.

No account is here taken of stress-difference brought about by the folding of the earth's crust or that due to residual effects of a state of very intense stress which may have been brought into existence at a very remote period of the earth's history.

(ii) *Collapse Due to Pressure in the Earth's Crust*

We have noticed in § 8 that the pressure at any point of the earth's crust may be roughly represented by the weight of a column of rock of that depth. If w represent the average weight of rock at the earth's surface per cubic cm. and h the depth in cms., a small spherical cavity can exist provided

$$wh<\tfrac{2}{3}S \qquad (26)$$

where S is the limiting stress-difference of § 6 expressed in grammes per sq. cm. Making use of the numerical values corresponding to a limiting stress-difference between 160,000 and 200,000 pounds per sq. in. (1.13×10^6 and 1.41×10^6 grammes per sq. cm.) for Westerly granite and taking 2.7 as the mean density of surface rocks, we can assert that small cavities in the earth's crust will not collapse provided the depth does not exceed a quantity h whose value lies between 27.7 and 33.7 kilometers (h between 17.2 and 20.9 miles). This estimate is several times greater than that deduced by Hoskins,[1] the reason being that it is necessary to make use of a very much higher value of limiting stress-difference than that employed in the investigation referred to. Even at a temperature of 550° C. which is supposed to exist at a point 11 miles below the earth's surface, Adams has shown that S is greater than 95,000 pounds per sq. in. which corresponds to a depth of 15 miles. Any internal pressure in the cavity (due to water-pressure, steam, etc.) would increase the above estimate for the depths at which cavities can exist.

The *size* of a cavity which can exist at a given depth depends on considerations of *stability* and would demand a separate investigation.

[1] Hoskins, *op. cit.*, 859. Hoskins expresses the result of his investigation in the form "cavities must certainly close up if $wh>S$." The value for S is taken to be 25,000 pounds per sq. in. The much higher value between 160,000 and 200,000 pounds per sq. in. indicated by experiments on Westerly granite shows that Hoskins' estimate for the depth at which cavities must close, must be increased between 7 and 8 times.

§ 10. SUMMARY AND CONCLUSIONS

1. Secs. 1 to 3 are devoted to a mathematical discussion of the state of stress existing in cylindrical rock specimens incased in heavy nickel-steel jackets and described by Dr. Adams in an accompanying paper.

2. In sec. 4 it is shown that observations on the radial strains of the nickel-steel jacket agree well with the calculated values as long as the load does not exceed a certain value; beyond that point the results of experiment indicate a change in the elastic constants with load; an analysis of observations of this type could be made to give a relation between the rigidity and the load for stress-differences beyond the elastic limit. The results of sections 4 and 5 also give a good account of the manner in which the rock specimens break down under load.

3. The experimental results of Dr. Adams discussed in sec. 6 of the present paper show that in the neighborhood of a small cylindrical cavity, in a specimen of Westerly granite, no flow or set takes place when the stress-difference amounts to as much as 160,000 pounds per sq. in. The cavity just begins to break down for a stress-difference of 200,000 pounds per sq. in. We therefore assign to the limiting stress-difference in the neighborhood of small cavities in rocks typical of that forming the greater part of the earth's crust, a value S between 160,000 and 200,000 pounds per sq. in. for ordinary temperatures.

4. Secs. 7 to 9 deal with the existence of cavities in media under stress with especial reference to the depth at which cavities in the earth's crust can remain open.

It is shown that no state of shearing stress in the crust of the earth, due to the weights of continents and mountains can cause the collapse of the rock in the neighborhood of a small cavity.

It is also shown that as far as hydrostatic pressure in the earth's crust is concerned a small cavity at ordinary temperatures will remain open provided the depth does not exceed a value between 17.2 and 20.9 miles. At a temperature of 550° C. supposed to exist 11 miles below the earth's surface, cavities will remain open when submitted to considerably greater pressures than are found at this depth. These values greatly exceed previous estimates because

experiment shows that a much higher value of limiting stress-difference than that usually employed must be taken in the neighborhood of small cavities.

5. The *size* of a cavity which can exist at a given depth depends on considerations of *stability* and would demand a separate investigation.

January 30, 1912

AN OLD EROSION SURFACE IN IDAHO: ITS AGE AND VALUE AS A DATUM PLANE[1]

JOSEPH B. UMPLEBY

THE EROSION SURFACE

Evidences of a former erosion cycle.—A plateau surface has long been recognized in Idaho, and over much of the state it has been described as a feature of erosion. The observations of the writer have been confined to an area of about 5,000 square miles in the eastern part of that great highland mass known as the Salmon River Mountains, but the literature shows that a description of this area is applicable to much of the state.

The Salmon River Mountains are characterized by deep canyons separated by even-crested divides, which here and there widen out into broad flats. Within the region there is not only a striking accordance of summit levels; there is a general continuity of level summit areas. Plateau remnants several square miles in extent are not uncommon. One of these is Poverty Flat near Challis in Custer County. It is a comparatively level tract of about 25 square miles, and occurs at an elevation 9,600 feet above sea (Fig. 1). Bordering it are narrow valleys as much as 5,000 feet deep, but beyond them high, even-crested ridges and occasionally flat areas continue to the horizon in every direction. The rocks forming this flat are steeply tilted schists, slates, and quartzites, the latter

[1] Published by permission of the Director of the U.S. Geological Survey.

here and there forming low hills. Near Leesburg, in Lemhi County the plateau surface is also well preserved. Here it is about 8,500 feet in elevation, and breaks off abruptly along the canyon of Salmon River, which flows in a gorge 5,500 feet deep.

Equally significant with the high flat-topped areas are the innumerable level-crested divides which extend out from them, and with other more isolated summits form a veritable labyrinth of highland tracts. Also worthy of note, as indicating that streams once flowed near the summit levels, are occasional rock-cut terraces which parallel the plateau surface but at slightly lower

FIG. 1.—A portion of Poverty Flat, which has an elevation of 9,600 feet, and is bordered by canyons as much as 5,000 feet deep. The spur on the right shows the highly inclined beds across which the flat is developed.

levels. One of these occurs along the west side of Spring Mountain, and another along the south side of Poverty Flat.

These several features clearly indicate a plateau surface, now deeply dissected, and when it is remembered that it is cut across highly inclined rocks of diverse composition, it seems equally clear that it could only have been developed by profound erosion. The region was reduced to gentle relief, and later raised to its present elevation.

Correlation and extent.—Mr. Lindgren describes the same surface in west-central Idaho, and concludes that[1] "The whole mountain region should probably be regarded as a vast plateau. . . . . The uplift of this plateau and its intricate and deeply cut drainage system evidently antedate the Miocene period." These high-

[1] Waldemar Lindgren, *Twentieth Annual Rept., U.S. Geol. Surv.*, Pt. III (1900), 77.

lands extend to the north, and in speaking of them the same writer says:[1] "Their combined crest-line would form an undulating plain differing little in elevation in the various parts of the Clearwater Mountains. From their westerly margins the mountains slope rapidly to the lava plateau, which has an elevation of 3,000 to 3,500 feet. . . . . Along Salmon River the high mountain plateau extends farther westward, and its last ramparts overlook the great bend of that river, rising 6,500 feet above its water line." Mr. Lindgren's conclusion is that "We must regard this surface as the result of erosion. The country was worn down to a comparatively gentle topographic feature, then uplifted and deeply dissected by canyons."

Mr. Calkins[2] describes the Coeur d'Alene Range, still farther north, as having a "general aspect similar to that of a maturely dissected plateau." He describes also the Cabinet and Purcell ranges in western Montana, in similar terms. East of these, Mr. Willis[3] recognized a peneplain over the Galton Range, and suggests that it may continue eastward over the Livingston and Lewis ranges. Northward in British Columbia the Interior Plateau is described by G. M. Dawson[4] as an elevated peneplain of Eocene age. South of this the writer[5] recognized what was thought to be the same surface at Republic, Washington.

The extent of the old erosioned surface can only be outlined in a general way because of the many localities where its identity has been destroyed and the broad areas which have not been studied physiographically. The above citations show, however, that a plateau surface cut across greatly disturbed beds extends over much of Idaho and into adjoining parts of Montana, Washington, and British Columbia. The areas in Idaho are continuous; those elsewhere are more isolated, but that all date from the same cycle of erosion will appear rather obvious during the later discussion.

Elevation and preservation.—The combined crest lines of the plateau areas in Idaho would form an undulating plain which

[1] Waldemar Lindgren, *P. P. 27, U.S. Geol. Surv.* (1904), 14.

[2] F. C. Calkins, and D. F. MacDonald, *Bull.* 384, *U.S. Geol. Surv.* (1909), 14, 19.

[3] Bailey Willis, *Geol. Soc. Amer.*, XII (1901), 349.

[4] G. M. Dawson, *Trans. Royal Soc. Canada* (1890), 13.

[5] J. B. Umpleby, *Wash. Geol. Survey, Bull. I* (1910), 11.

reaches its maximum elevation of about 10,000 feet along a course through Gilmore and Challis. Northwestward it grades off to 8,500 feet in the north part of Lemhi County, and thence to about 7,000 feet in the Clearwater Mountains. This elevation is also common in northwest Montana, but westward in the Colville Mountains and on north in the Interior Plateau the summits are about 5,000 feet above sea.

Faulting and folding have affected the plateau area of central and eastern Idaho since its last elevation, but through all, the integrity of the old surface has persisted in a remarkable degree. Local prominences above the general level, though not characteristic of the region, occur. Some of these are undoubtedly erosion remnants, but others probably involve faulting, and some may be due to folding. In western Montana the old surface appears from the literature to be far less perfectly preserved. In northeastern Washington and in British Columbia it is also preserved imperfectly. Here there is a remarkable accordance of summit levels, but no large plateau remnants, such as those in Idaho, have been described.

Age of the Surface

Evidence from the area.—After the last general elevation of the region great valleys were developed, and in these extensive lake beds accumulated during the Miocene period. Such deposits occur at Salmon, Idaho,[1] in western Montana,[2] at Republic, Washington,[3] and at various places in the Interior Plateau of British Columbia.[4]

Allowing the Oligocene for the development of the broad valleys occupied by the Miocene lake beds, the old erosion surface is pre-Oligocene. On the other hand, it cuts all the older formations of the region including the granite, which is post-Triassic. Thus from evidence within the plateau region the old erosion surface is pre-Oligocene and post-Triassic.

[1] J. B. Umpleby, *Bull. U.S. Geol. Surv.* (now in manuscript).

[2] Earl Douglass, *Mont. Univ. Missoula, Mont.*, 27 pp., 4 plates, 1899; *Carnegie Mus. Annals*, V (1909), 159-65.

[3] J. B. Umpleby, *Bull. I, Wash. Geol. Surv.* (1910), 11.

[4] G. M. Dawson, *Trans. Royal Soc. Canada* (1890), 14.

Evidence from nearby areas.—It is thought that adjoining regions afford further evidence as to the age of this surface. Extensive deposition is a corollary of profound erosion, hence we should expect to find a sedimentary record of the cycle of erosion represented by the present plateau surface. The Rocky Mountain

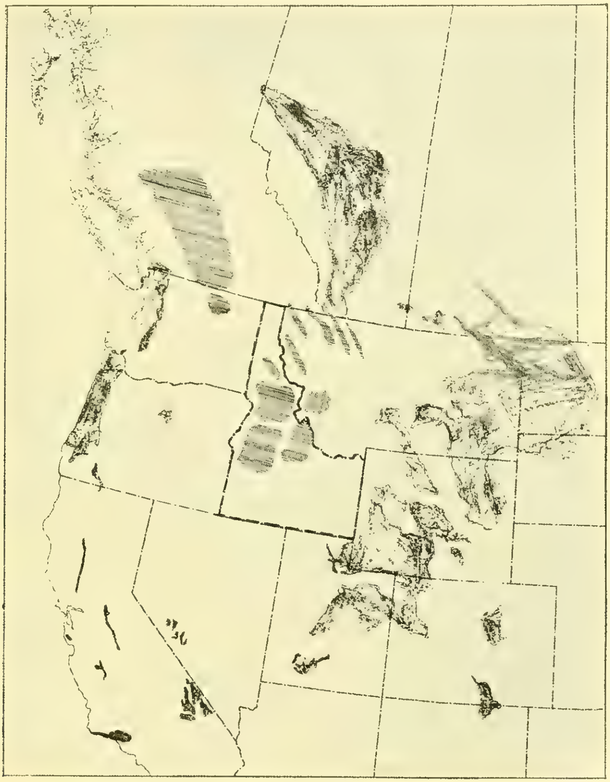

FIG. 2.—The figure illustrates the distribution of Eocene sediments in the Northwest. The horizontal lines indicate areas which have been described as of the plateau type. The area of vertical lines is similar but is based on oral communications. Adapted from the Geologic Map of North America, with the plateau areas added.

region is known to have supplied vast volumes of sediments during the Cretaceous, but not until the Eocene does the distribution of sediments bear a significant relation to the present plateau area. Fig. 2 illustrates the distribution of the Eocene sediments in the

Northwest and the parallel lines of the same figures show the position of the areas described as representing the plateau type. The distribution of Eocene sediments around these areas strongly suggests a relation between the two. It seems that the sediments could not have been derived from the region after its last elevation for two reasons: (1) It is very doubtful if the plateau is sufficiently dissected to afford the volume of material represented by the Eocene beds, and (2) All the more important valleys of the area drain westward, and in all probability have done so throughout their entire history. This is true of the Rocky Mountain trough, the Purcell trough, and the Snake, Salmon, and Columbia river channels. These, together with their tributaries, represent perhaps 90 per cent of the present dissection of the plateau region. If we assume that the old erosion surface is pre-Eocene the material derived from these several valleys may be thought to account for the narrow fringe of Eocene sediments on the west, but cannot account for the incomparably more extensive Eocene beds which lie to the east of the present plateau region.

Conclusion.—From this line of evidence it is concluded that the Eocene sediments were derived from the plateau area during that great cycle of erosion which resulted in a comparatively level surface, and therefore that the plateau region of the present day was characterized by gentle topographic features at about the close of the Eocene period. Whether or not that former great cycle of erosion began with the Eocene may be an open question, but that it closed with the Eocene, and therefore that the present plateau surface is of Eocene age, there seems to be little room for doubt.

The Eocene Surface as a Datum Plane

Over much of Idaho no satisfactory datum plane has been recognized between the Algonkian and the Pleistocene. In the southeastern part of the State formations of Paleozoic age are present and along the western side are the great sheets of Miocene basalt. Other datum planes are recognized, but they are all well removed from the plateau area. Thus where a datum plane is most needed the Eocene erosion surface is best preserved.

The value of this surface in time determinations is perhaps greatest in dating the ore deposits of the plateau region. Two distinct periods of mineralization are recognized in this area. The earlier deposits are cut by the Eocene surface, but the later are inclosed in or associated with eruptive rocks which fill valleys developed after its elevation. Thus the Eocene surface was developed during the interval between two great periods of mineralization. Reasoning from it as a datum plane the deposits may be rather definitely placed in time. On the one hand is the Pleistocene glaciation and the amount of erosion which preceded it but followed the veins, thus placing a fairly definite limit. On the other the granite, which is older than the earlier veins, is assigned to the latest Cretaceous or earliest Eocene as brought out in the next section.

Age of Granitic Intrusions Suggested by the Eocene Surface

There are many granitic batholiths within the plateau region. The largest of these is the one in central Idaho, which is more than 20,000 square miles in extent. Several others approach to or exceed 1,000 square miles in area, and those of smaller size are to be numbered by the score. Indeed, probably one-third of the surface rock throughout the present plateau region is granite or closely allied batholithic types. Both broadly and locally these intrusions vary from normal granite through soda granite and quartz-monzonite to quartz-diorite. Their distribution is shown by Fig. 3. A comparison of this with Fig. 2 brings out the striking accordance in distribution between the area of granitic intrusions and the plateau. Their coextent suggests a genetic relation between them, but the granite constitutes a larger part of the plateau surface; hence, if a relation exists it must date from the earlier part of the erosion cycle during which the Eocene surface was developed. The problem, therefore, is to show whether the granite entered at this or at a still earlier time. Probably most geologists will agree in the opinion that such a tremendous volume of magmatic material did not enter beneath the region without causing or accompanying a profound elevation of the

surface; yet the area of granitic intrusions does not show a significant relation to surrounding sedimentary deposits until the Eocene. It is believed, therefore, that the granite intrusions accompanied the elevation which initiated that great cycle of erosion which

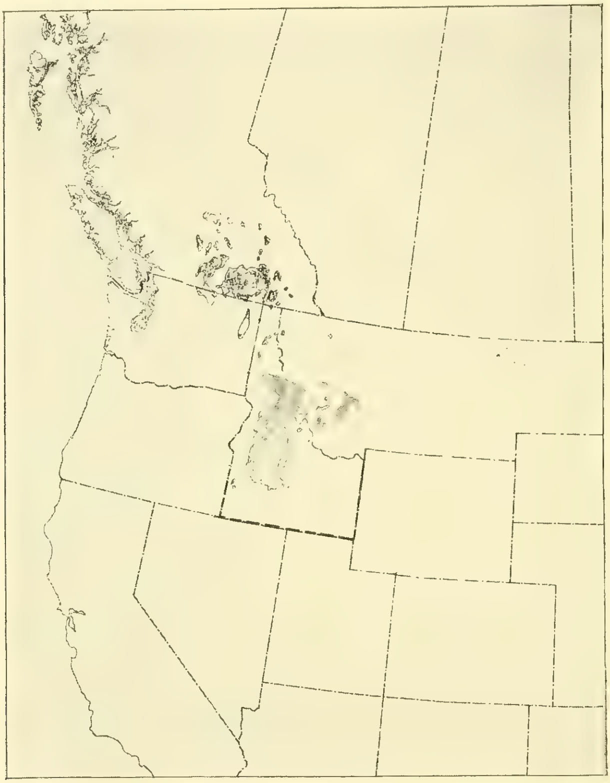

FIG. 3.—The figure shows the distribution of granitic rocks in the plateau region. Adapted from the Geologic Map of North America.

resulted in the Eocene surface. The granite batholiths of the plateau region therefore are assigned to the late Cretaceous or early Eocene.[1]

[1] Since this article was prepared, Mr. Adolph Knopf has told the writer that during recent field work he found the Butte granite to cut andesites which should probably be correlated with the Livingston formations. Mr. F. C. Calkins also has found the granite intrusions of the Phillipsburg quadrangle, Mont., to be post-Colorado. Thus recent geologic studies support conclusions and suggestions herein set forth.

Summary

The principal problems discussed in this paper fall under four headings, as follows:

1. An old erosion surface which may prove to be a peneplain, but which because of inadequate study is not so defined here, extends over much of Idaho and into adjoining parts of Montana, Washington, and British Columbia.

2. The surface is assigned to the Eocene because of the relation of Miocene lake beds to it and because of its relation to Eocene deposits.

3. The Eocene surface forms a valuable datum plane in broad areas where time relations between the Algonkian and the Pleistocene are otherwise obscure.

4. It is suggested that the great granitic batholiths of the plateau region either initiated or accompanied the initiation of the cycle of erosion which resulted in the Eocene surface and hence, that they are of late Cretaceous or early Eocene age.

EUGEN HUSSAK

MIGUEL A. LISBOA[1]

Professor Eugen Hussak died in a little hotel in the city of Caldas in southern Minas Geraes, Brazil, on the fifth of September last. The important part he took in the development of mineralogy and petrography in Brazil, his standing among specialists, and his scientific attainments call for a fuller account of his life and labors than we are able to give at the present.

Francis Eugen Hussak was born at Wilden, Steiermark, Austria, March 10, 1856. His parents were Johann Hussak, a lawyer, and his wife Therese von Wagner. After he came to Brazil he married Herminia Hennies by whom he had two sons. He was educated in the Gymnasium and University of Gratz, studied afterward at the University of Leipzig, where he was a pupil of Ferdinand Zirkel, one of the founders of the modern science of petrography, and later returned to Gratz where he took his Doctor's degree. While working under Zirkel at Leipzig, Hussak began the microscopic study of minerals and rocks, and it was from him that he received his greatest inspiration and encouragement. After graduation he went to Vienna where he attended the lectures of Tschermak, and was for three years engaged on the K.K. Geolog. Reichsanstalt. In Vienna he prepared his book *Anleitung zur Bestimmung der gesteinsbildenden Mineralien* which was published at Leipzig in 1885, a book that was translated into English by Professor E. G. Smith, and was published in the United States in

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[1] Translated from the Portuguese by J. C. Branner. The original article appeared in the *Jornal do Commercio*, Rio de Janeiro, October 7, 1911.

1893 under the title of *The Determination of Rock-forming Minerals*. He was then called to Germany as assistant to Professor D. Laspeyres and in that capacity worked at Kiel and later at Bonn. He remained in Germany until 1887, publishing in the meantime his *Katechismus der Mineralogie*, a book which has passed through five editions.

In the universities and museums of Germany and Austria Hussak had examined various collections of Brazilian rocks and minerals that had been put aside to await classification. At Vienna he saw the collections made by Helmreichen, in Bonn he saw those made by Krantz, and at Berlin he saw a collection from Rio Grande do Sul. In all these collections he saw much interesting material, and Brazil seemed to him a new land of promise. But Hussak was not a man who cared to work over the ground or materials left by others, and he took no pleasure in finding fault with the work of others. He preferred new fields. Brazil offered such an opening and whether and when he would go there was only a question of opportunity. He chanced to have as one of his pupils at Bonn a young Brazilian named Jordano Machado. A collection of nephelene rocks taken from a railway tunnel on the Mogyana Railway near the city of Caldas had been sent Jordano Machado, and he had chosen the collection for the subject of his thesis. Hussak looked after the preparation and publication of this paper with great care and interest. Every one of the microscopic rock slides was examined by him personally and carefully. The thesis of Jordano Machado was a brilliant success, but the young petrographer eventually gave up his petrographic work in order to raise coffee.

At this point Hussak left his professorship in the university and went to Brazil with his pupil, who extended to him the cordial Brazilian hospitality of his father's coffee plantation. His early experiences in Brazil were rather trying. On the coffee plantation there was really nothing for a mineralogist to do. Besides there he had no outfit for such work; he lacked microscope, slides, laboratory, and all. After some months of this he felt that he must return to Germany; but unfortunately he had not even the means for the voyage.

In the palace of Dom Pedro II, the emperor of Brazil, he found a temporary solution of the problem. Someone told the emperor that a mineralogist whom Rosenbusch spoke of very highly was in the country without occupation. This led to his being engaged to give instruction in mineralogy and petrography to Dom Pedro de Saxe, the emperor's grandson. But the lessons were soon interrupted. The pupil wanted to get on too fast. Dom Pedro de Saxe wanted to begin his studies by the publication of original papers. His Austrian instructor coolly told him that it was too early yet; that one should learn before he began to teach. The young prince was offended; the teacher insisted, and the matter ended with his being shown the door.

Hussak was living at that time at the old Beresford Hotel in Petropolis in front of the imperial residence. He went to his rooms and began preparations for leaving the city that same day. He was a simple man, and in the crises of life he was at times a mere child. He frankly told the keeper of the hotel of his humiliation, and of his financial difficulties. The hotel-keeper was more philosophical about the matter; he consoled the professor, but did not allow him to leave.

The next morning Dr. Stoltz knocked at Hussak's door, bringing an invitation from the magnanimous emperor for him to appear at the palace. Hussak went at once, and if any apologies were lacking from the young prince they were more than made up by his Imperial Majesty himself. So the lessons were continued for a while at least.

Later O. A. Derby engaged Hussak on the geological survey of the state of S. Paulo, and for twenty years he was the leading petrographer of Brazil.

A glance at the bibliography of Eugen Hussak shows a remarkable originality in his work. To be sure, the backward condition of petrographic geology in Brazil contributed largely to this originality. Mineralogy and petrography were sciences but little cultivated among us. Such work had been begun here by Gorceix in the School of Mines at Ouro Preto, but when the Austrian professor came to S. Paulo there was really no one in the country who was acquainted with the details of the technique of modern petro-

graphy. In S. Paulo there came together, by accident it may be said, a geologist, a petrographic mineralogist, and a chemist, each of them a leader in his specialty. These men were Derby, Hussak, and Florence. They were to work together, and each was to place at the disposal of the others the resources of his own science.

It may be said of Hussak that all his works were contributions to science. He described a large number of new minerals, notably, brazilite, lewisite, zirkelite, tripuhyte, derbylite, senaite, florencite, chalmersite, and gorceixite. He also pointed out various mineral substances of economic importance, such as oxide of zirconium at Caldas, platinum in Minas, carbonados and diamonds in S. Paulo, corundum in Brazil and in Uruguay, and likewise cassiterite, monazite, and several others.

On mineral deposits he left two noteworthy contributions. These were his studies of the gold-bearing beds of Passagem, and on the occurrence of palladium and platinum in Brazil. When he made this last investigation, he wrote to Russian geologists who had sent him materials from the Ural region, calling their attention to certain facts that had hitherto escaped their notice. He began the systematic study of the heavy minerals of the diamond-bearing gravels and added much to the work that had been done by Gorceix. On this subject he has left much valuable material unpublished.

Many years ago he began the preparation of a mineralogy of Brazil, and from the large amount of original matter published by him on this subject, from the many unpublished observations that he had put aside for this work, and from the ability he showed in the preparation of a book for instruction, it is evident that such a volume would have embraced all of his work as a mineralogist. Unfortunately this important work is lost with him.

Wherever he was known he has left sincere friends. In Brazil he leaves no successor.

THE PETROGRAPHIC CHARACTER OF OHIO SANDS WITH RELATION TO THEIR ORIGIN[1]

D. DALE CONDIT
Geological Survey of Ohio, Columbus

In connection with a report in preparation by the Geological Survey of Ohio on glass and molding sand, a petrographic examination of a large number of samples was made by the writer of this paper. The samples were collected from all parts of Ohio and represent practically all the important deposits of the state from the oldest to the very recent. About ninety rock samples, Carboniferous and older, were examined, and forty uncemented, recent sands from the glacial drift and other sources. The petrographic work was done in the geological laboratories at Columbia University.

In preparing the samples for inspection with the microscope, thin sections were made of the rocks. Most of these had only a slight bond so they were first boiled in Canada balsam until all the interstices were permeated by that liquid. On cooling there resulted a firmly cemented mass which would permit of grinding to the usual thickness. In the case of loose, uncemented sands, liquid mounts were made in oil of cloves which has an index refraction similar to that of balsam. Many of the samples being made up of grains too thick for study with polarized light were first crushed to 100-mesh size in an agate mortar, after a preliminary inspection had been made to determine the shape and size of grain.

The sands ordinarily met with in Ohio may be divided into three great groups on the basis of physical properties and mineral make-up. The three groups are: (1) The old sandstone formations Permo-Carboniferous and older; (2) residuary and outwash deposits derived by weathering and erosion of the sandstones; (3) glacial drift sands—recent deposits made up of assorted material

[1] Published with permission of the State Geologist of Ohio.

obtained from the drift by the action of wind and water currents. Each group has certain physical and mineralogical features which are quite characteristic of the sand wherever found and which will be described.

The old sandstones of Group 1 are made up of travel-rounded grains cemented more or less firmly by silica, limonite, hematite, or some other bond. Quartz is by far the most abundant mineral. The accessory constituents seldom make as much as 15 per cent of the sand. They are minerals of a rather stable nature together with secondary products derived from the decompositon of the less stable original minerals. Orthoclase and plagioclase are as a rule much decomposed and their presence is shown by aggregates of sericite, kaolinite, and secondary quartz. Occasionally plagioclase grains are seen which still show twinning lines. Microcline is almost invariably fresh and unaltered. Tourmaline is common. Muscovite is widely distributed, being found in nearly every sand, but biotite is rare. Amphibole and pyroxene are almost entirely altered to chlorite, limonite, and other secondary products. No garnet was found in any of the sandstone samples. A sand from the Sharon Conglomerate of Summit County is regarded as representative of the group and its mineral list follows. The minerals are listed in order of abundance.

1. Quartz	8. Plagioclase
2. Muscovite	9. Sericite
3. Kaolinite	10. Hematite
4. Microcline	11. Apatite
5. Zircon	12. Chlorite
6. Limonite	13. Rutile
7. Orthoclase	

There is a slight bond of sericitic kaolinite and limonite. Some of the quartz grains show slight secondary growth. The feldspars are almost entirely altered and their outline is preserved by aggregates of sericite, kaolinite, and secondary quartz which are so interlocked as to resemble a mosaic pattern.

The Sylvania (Silurian) formation of northwestern Ohio is a good illustration of a very pure sand having few accessory minerals. A sample from Lucas County was found to contain only quartz,

calcite, dolomite, rutile, and apatite. The calcite and dolomite occur as minute rhombohedrons which serve as a cementing material. The rutile and apatite are needle-like inclusions in the quartz. The quartz grains average about 0.3 mm. in diameter and are nearly spherical in outline. A chemical analysis shows 95.11 per cent of silica.

There is a number of secondary minerals which have found place in the old sandstones of Ohio subsequent to their deposition. Some of these have resulted from decomposition in place of original minerals while others have been brought in from foreign sources and precipitated from solution. Some of the secondary minerals due to precipitation from solution are: secondary quartz, hematite, limonite, calcite, dolomite, siderite, pyrite, and marcasite. Some of the alteration products of original minerals are: kaolinite, sericite, chlorite, secondary quartz, leucoxene, limonite, and hematite.

The sands of Group 2, derived by weathering and erosion of the old sandstones, are usually loose, uncemented deposits that occur as a residuary mantle on the upland or as bar deposits along ancient and modern valleys. Such sands may be made up of rather angular grains, especially if there was silicification of the sandstone whose weathering furnished the material. A coating of iron oxide on the grains is quite characteristic. This may be so thick as entirely to conceal the interference colors of the quartz when viewed under crossed nicols. The minerals of residual sands are fewer than those in the original sandstone. Solution and erosion incident to weathering eliminate many of the accessory constituents and as a result minerals other than quartz and limonite are few. Such materials when favorably situated might be reworked by wind and water currents to form very pure quartz sand deposits comparable with the Sylvania.

So much of Ohio is covered by glacial drift that most of the modern river sands are a mixture of contributions from local sources and from the drift. There are, however, a few counties in the southeastern part of the state which have sand deposits obtained entirely from local sandstones with no contributions from the glacial drift. These deposits are found along both modern and

pre-Glacial drainage channels. In Gallia County is an ancient, abandoned valley which forms a prominent topographic feature and has been traced for many miles by Tight,[1] who has named it the Marietta River. A sand sample taken from a bar deposit in this valley has the following mineral make-up: quartz, limonite, zircon, tourmaline, apatite, and kaolinite. All of the grains are thickly coated with limonite.

The sands of Group 3, derived by assortment of the Glacial drift, are usually of a very heterogeneous nature both as to shape of grain and mineral composition. There are sharp, angular particles with freshly fractured surfaces that have evidently resulted from the crushing and granulation of rock masses. There are also well-rounded grains that represent sand deposits in the path of the advancing ice front which were carried along and blended with the comminuted rock material. During the recession of the ice and subsequently, wind and water currents have assorted much of the drift into gravels, sands, and silts. In the northern part of the state are fine-grained sands and silts that have been deposited in the shallow waters of recessional lakes. These sands are remarkably well assorted. Extensive deposits in Erie County are found suitable for molding sands. In one sample the diameter of grain was found to range between 0.3 and 0.06 mm. with 0.1 mm. as an average. Only the largest grains show any rounding. Another sample was made up of sharp grains ranging from 0.05 mm. down to mineral flour.

As to mineral content the glacial drift sand is quite distinct from the preceding groups. Quartz is still the most abundant mineral, but there is almost always a high percentage of accessory minerals. Many of these are of a perishable nature and cannot withstand solution and decomposition incident to long weathering. Outcrops of crystalline metamorphic rocks beyond the Great Lakes may be regarded as the source of such minerals. Probably 90 per cent of the drift in any one locality is made up of materials derived from within fifty miles of that point but there is quite invariably a

[1] W. G. Tight, "Drainage modifications in southeastern Ohio and adjacent parts of West Virginia and Kentucky," *Professional Paper U.S. Geol. Surv. No. 13*, p. 76; also Plate XI.

portion which, by its mineral content, shows derivation from the crystalline rocks. A number of minerals entirely wanting in the old sandstones are found fresh and little altered. Garnet, diopside, augite, enstatite, hypersthene, hornblende, actinolite, cyanite, and free grains of magnetite are abundant in the drift. Of these garnet, diopside, augite, enstatite, hypersthene, and cyanite are not found in the old sandstones and the others are rare. The former presence of abundant ferromagnesian minerals is indicated by chlorite, saussurite, and other alteration products.

The character of the glacial sand type is well shown by a fine-grained sand from near Sandusky, Ohio. The bed is regarded as an off-shore deposit in Lake Warren.[1]

MINERALS IN ORDER OF ABUNDANCE

1. Quartz	10. Tourmaline
2. Garnet	11. Zircon
3. Diopside	12. Limonite
4. Hornblende	13. Kaolinite
5. Enstatite	14. Apatite
6. Microcline	15. Sericite
7. Plagioclase	16. Epidote
8. Orthoclase	17. Magnetite
9. Hypersthene	18. Rutile

The sand is made up of angular grains with surfaces that show recent fracture. The size grades from 0.05 mm. diameter down to mineral dust. There is little limonite coating on the grains. Garnet, diopside, enstatite, hypersthene, hornblende, and feldspars are the principal accessory minerals and none of these are much decomposed.

The characters of the three great sand types may be summarized as follows: The rock sands (all Paleozoic) are made up of travel-rounded grains more or less firmly cemented. The minerals are those of a stable nature together with some which have been derived by the alteration of less stable original minerals. Ferromagnesian minerals are almost entirely wanting. The residual sands and outwash deposits derived from erosion of the sandstones are made up of products that represent the final

[1] Frank Leverett, Monograph 41, *U.S. Geol. Surv.*, Plate XXII.

results of weathering. Many minerals present in the sandstones have been eliminated and there remains little besides the quartz, which is itself usually heavily coated with limonite. The glacial drift sand is a hodgepodge mixture of anything that happened to be in the path of the ice. Travel-rounded grains derived from sand deposits are mixed with sharp particles produced by the comminution of rock. Minerals of an unstable nature recently derived from the crystalline rocks are abundant and these show little alteration.

MINERAL SUMMARY

Thirty-four minerals have been recognized in Ohio sands. Some of these are abundant in practically every sample while others are less widely distributed and are only present in small amounts. While the samples were taken from all parts of the state from sands of all ages they can hardly be regarded as representative of many of the formations because only those outcrops which appeared suitable for glass or molding were sampled. A list of the minerals is given with notes as to the occurrence of each.

MINERALS OF OHIO SANDS

Quartz	Garnet
Orthoclase	Corundum
Plagioclase	Magnetite
Microcline	Ilmenite
Hornblende	Leucoxene
Actinolite	Titanite
Diopside	Monazite
Augite	Xenotime
Enstatite	Hematite
Hypersthene	Limonite
Muscovite	Kaolinite
Sericite	Chlorite
Tourmaline	Serpentine
Zircon	Epidote
Apatite	Calcite
Rutile	Dolomite
Biotite	Pyrite

Quartz.—Quartz is by far the most abundant mineral in all sands examined. It usually constitutes over 90 per cent of the make-up of the old sandstones. Only twelve out of ninety-one samples examined contained less than 90 per

cent of quartz. The most impure sandstone inspected had about 75 per cent. The purest sand on analysis showed a little more than 98 per cent of quartz.

Quartz is also the principal mineral in sands selected for molding purposes but in some cases it is slightly less than the sum of all the accessory minerals. In glacial drift sands it usually ranges from 50 to 70 per cent. It may constitute as much as 90 per cent of residual sands derived from weathering of the sandstones.

Feldspars.—Feldspars probably rank next to quartz in abundance and distribution. About three-fourths of the sandstone samples have feldspar. Plagioclase was recognized in one-fourth of the rock samples and orthoclase in one-fifth. Both are almost invariably much decomposed and in many cases can only be called "much-altered feldspar" without closer identification. Microcline is present in more than one-half of the samples and is one of the principal accessory minerals. It shows little decomposition even in the oldest sandstones. In the most arkosic sandstones of Ohio the feldspar content is usually less than 10 per cent.

The glacial drift sands have a large percentage of feldspar. This may be as much as 25 per cent in some cases. Orthoclase and plagioclase showing little or no decomposition are common. These minerals are entirely wanting in the residual sands but microcline is occasionally found.

Amphibole.—Hornblende and actinolite, the common varieties of amphibole, are almost entirely limited to the recent sands. Nearly every glacial drift sand contains actinolite and a lesser amount of hornblende. A few of the sandstones have much decomposed remnants of what appears to be actinolite. That these minerals were formerly present in many of the sandstones is shown by chlorite and other alteration products.

Pyroxene.—The common varieties of pyroxene in sands are diopside, enstatite, and hypersthene. Augite is less common. All are limited to recent sands of glacial drift origin. No pyroxene was seen in the sandstones but its former presence is indicated by alteration products.

Mica.—Muscovite flakes visible without a microscope are present in about two-thirds of the sandstone samples and one-half of the uncemented sands. Sericite is a common product from the alteration of feldspars. Biotite is rare even in the glacial drift sands.

Tourmaline.—This is very widely distributed. It was found in nearly three-fourths of the samples examined.

Zircon.—Zircon is nearly always present. It was found in over four-fifths of the samples.

Apatite.—About one-half of the samples were found to contain apatite. Both inclusions and free grains are common.

Rutile.—Nearly every sand has a small amount of rutile. Microscopic hairlike inclusions in quartz and free grains are the modes of occurrence.

Garnet.—Garnet is one of the principal accessory minerals of glacial drift sands. It was not found in any of the sandstones or residual sands.

Corundum.—Corundum is occasionally found in sands of all ages.

Magnetite.—More or less magnetite is always present. It is found both as free grains and inclusions in other minerals. In the glacial drift sands it is a prominent constituent.

Ilmenite and leucoxene.—Ilmenite is sometimes mixed with magnetite. Its presence is shown by leucoxene, an alteration product.

Titanite.—Titanite is occasionally seen in the recent sands of glacial drift origin.

Monazite.—Monazite is sparingly distributed in very small amounts in Ohio sands. It was noticed in three recent sands and seven sandstones.

Xenotime.—Xenotime is occasionally found in small amounts in sandstones near the base of the Coal Measures and in residual sands derived from these. It was noticed in twenty-two rock samples most of which were taken from the Sharon Conglomerate.

Hematite.—Hematite is quite common as inclusions in quartz. Earthy red hematite is sometimes a cementing material in sandstones.

Limonite.—Limonite is always present. It is a common cementing material in sandstones. In most of the sandstones examined the limonite content is less than 2 per cent. The grains of residual sands are usually thickly coated with limonite.

Kaolinite.—Kaolinite is a prominent constituent of most sands. In feldspathic sandstones it may constitute several per cent of the make-up.

Chlorite, serpentine, epidote.—These are of common occurrence in the Carboniferous sandstones. They are largely responsible for the greenish and bluish colors so often seen in those rocks.

Calcite and dolomite.—These were found as cementing material in the Sylvania sandstone of northwestern Ohio. Slight amounts, probably comminuted limestone, are sometimes seen in the glacial drift sands.

Pyrite.—No pyrite was seen in the sand samples but small limonite stained cavities probably due to oxidation of pyrite were seen in one sandstone. It is common in the deeper workings of quarries.

One of the interesting features brought out by the investigation is the entire absence of garnet in the old sandstones of Ohio. Inquiry and personal search show that this is not a local condition but that the scarcity or absence of garnet in the older sandstones is prevalent in widely separated regions. The West Virginia Geological Survey has recently made a petrographic examination of about thirty sandstones and garnet was found in only one of these—a sample from the Dunkard series.[1] Dr. A. A. Julien, whose study of sands has been very extensive, writes: "The

[1] G. P. Grimsley, "Iron Ores, Salt and Sandstone" *West Virginia Geol. Surv.*, IV (1909), 447.

scarcity or absence of garnet in the older sandstones generally prevails, I think, in all regions. I first recognized this in the Carbonic sandstones of Great Britain and soon afterward in those of Arabia Petræa and of northern Africa. It is also markedly absent or rare in the St. Peter, Cambrian, and older quartzites of this country."

In order to obtain data as to the occurrence of garnet in the older sandstones of eastern North America, a number of rock samples were examined. These were taken from collections of the Geological Department of Columbia University, and represent most of the important sandstones of the Paleozoic of the Appalachian region. There follows a summary of the results:

Cambrian: (1) Etcheminian conglomerate, Hanford Brook, Nova Scotia. Zircon present. No garnet seen. (2) Feldspathic quartzite, contact with pre-Cambrian. Doe River, Tenn. Zircon, tourmaline, and microcline seen. No garnet. (3) Sandstone, Iron Mountain, Mo. Plagioclase and zircon found, also a few grains of garnet.

Ordovician: St. Peter sandstone, Iowa. No garnet.

Silurian: Sylvania sandstone, southern Michigan and northwestern Ohio. No garnet.

Devonian: (1) Oriskany sandstone, Huntington, Pa. Zircon, tourmaline, and plagioclase (little decomposed). No garnet. (2) Oriskany sandstone, Vienna, Ontario County, N.Y. Zircon and calcite. No garnet. (3) Catskill sandstone, Monkey Hill, Delaware County, N.Y. Zircon and tourmaline. No garnet. (4) Catskill sandstone, Mill Creek, Pa. Tourmaline and zircon. No garnet. (5) Catskill sandstone, Catskill Mountains. A large number of thin sections were examined. Quartzite pebbles were seen, showing that the formation was derived in part from the reworking of a previous sandstone. Considerable well-preserved feldspar, and much epidote and chlorite are present. No garnet was seen.

Carboniferous: (1) Pocono sandstone, Dungannon, Pa. Zircon, tourmaline, and titanite present. One grain of garnet was seen. It had a pitted surface as though affected by solution. (2) Pocono, Pottsville, Pa. Zircon and tourmaline. No garnet. (3) Mauch Chunk sandstone, Cave Gorge, Dungannon, Pa. Zircon, plagioclase, tourmaline. No garnet.

As was mentioned in a previous page, garnet was found in one sample from the Permian of West Virginia. The Triassic beds of New Jersey and Connecticut abound in garnet. The grains are always fresh appearing with little sign of solution or alteration.

In attempting to account for the scarcity or absence of garnet

in the older sandstones, these questions arise: Is it due to the inability of garnet to withstand solution and decomposition incident to weathering? Is garnet sufficiently resistant to the wear of travel to find a place in sands laid down at a distance from the source of supply? Or is the scarcity due to the derivation of the components of the sandstone from a region where garnet was not an important rock-forming mineral?

There is ample evidence that garnet is quite resistant to ordinary weathering processes. It is a common constituent of residuary sands derived from decomposed schists. The Newark series of New Jersey and Connecticut, consisting largely of coarse sandstone which would favor free circulation of ground waters, has been exposed to weathering processes for many ages; nevertheless it contains abundant garnet grains which show little evidence of solution or alteration. Furthermore the discovery of occasional particles in a few of the older Paleozoic sandstones is still stronger proof of the resistant properties of garnet. The scarcity cannot be due to mere decay since often other minerals survive which are equally or more susceptible to decay, such as feldspars and mica.

The physical properties of garnet are such that it should withstand the wear of long travel. Lack of cleavage, and hardness are in its favor. Zircon, tourmaline, feldspars, and other minerals which are somewhat similar in their physical properties to garnet are widely distributed even in the very old sandstones.

This leads to the conclusion that the materials of the older sandstones were derived from sources where garnet was not abundant. Repeated reworking of successive sandstones has doubtless furnished much of the material. Very pure quartz sands of the Sylvania type are probably entirely derived in that way. However, most of the great sandstone formations have constituents which have certainly come rather directly from crystalline areas. This is especially true of the Catskill series and the "Coal Measures" sandstones.

Garnet is a characteristic mineral of regional and contact metamorphism. It is common in gneisses and schists of sedimentary origin. As an original mineral in igneous rocks it is much less common. The gneisses and schists of the Appalachian region are

abundantly provided with garnet. Glacial drift drawn from such sources has so much of the mineral that it is second only to quartz in abundance. The Triassic beds of the east, fairly reeking with garnet, furnish an illustration of a sandstone built largely from materials derived rather directly from the crystallines. Conditions of sedimentation during "Coal Measures," Mauch Chunk, and Catskill time were probably not greatly different from those that prevailed during the formation of the Triassic beds. All are either continental or near shore in origin.

To the writer it seems that the difference in mineral content between the Triassic and the older sandstones indicates a quite different source of material. While it is obvious that gneisses and schists contributed very extensively to the Triassic beds, it seems probable that such rocks did not furnish much of the materials of the older sandstones. A large portion of these have doubtless come from crystalline sources, but the minerals indicate that the rock may have been igneous rather than metamorphic. It is conceivable that a peridotite or gabbro furnished the ferromagnesian minerals so abundant in the Catskill series, while a granite was the source of the zircon, tourmaline, and muscovite of the "Coal Measures" sandstones.

It is becoming more and more evident to geologists that the mountain-making processes which took place at the close of the Paleozoic were accompanied by the intrusion of extensive igneous masses and the metamorphism of the country rock into schists. The work of Loughlin[1] and others has demonstrated the magnitude of these changes in Rhode Island. A number of intrusive masses, mostly granite, in the highland region of New York and New Jersey, are known to be post-Ordovician and may be of the same age as those in Rhode Island. Recently a report has come from Virginia of the finding of fossils in schistose slates of the Piedmont belt. These slates were formerly regarded as pre-Cambrian but the fossils show them to be Upper Ordovician in age.[2] Thus it is

[1] G. F. Loughlin, "Intrusive Granites and Associated Metamorphic Sediments in Southwestern Rhode Island," *Am. Jour. Sci.*, XXIX (1910), 447–57.

[2] Thomas L. Watson and S. L. Powell, "Fossil Evidence of the Age of the Virginia Piedmont Slates," *Am. Jour. Sci.*, XXXI (1911), 33–44.

seen that as more detailed work is done in the region of the crystalline rocks, more and more of the "Complex" is differentiated and removed from the pre-Cambrian and proved to be more recent.

Is it not possible that the general scarcity of garnet in the older sandstones may be due to the more recent formation of many garnetiferous schists which are now classed as pre-Cambrian?

SOME OBSERVATIONS AND EXPERIMENTS ON JOINT PLANES

PEARL SHELDON

II

EXPERIMENTAL WORK

Systems of cracks at right angles to each other were obtained by Daubrée[1] by twisting plates of ice and glass and by compressing mixtures of beeswax and resin. W. O. Crosby[2] found that if plates twisted not quite to the breaking-point were given a shock they would break in cracks at right angles to each other. Systems of cracks due to torsion have been studied experimentally by G. F. Becker.[3] For this reason and because the conditions involved in the torsion experiments do not agree closely with the conditions under which the joint planes of this region were formed, these experiments were not repeated.

Theoretically and practically work similar to Daubrée's pressure experiments seemed most likely to give satisfactory results. Daubrée applied pressure over the square ends of blocks of wax. The sides were left unconfined so that deformation could take place on all sides. Besides large planes of slipping, the deformed blocks showed a network of fine even cracks at right angles to each other and parallel to the larger breaks. Daubrée compared the larger breaks with faults and the smaller with joints. Unfortunately, the outcrops of the cracks, though at right angles to each other, made angles of 45° with the direction of pressure, and, judging from his figures, the planes of breaking were parallel to the faces of an octahedron. This does not agree well with the commonly observed angles between joint faces, and the usual strike and dip relation of joints indicates that they are nearly at right angles to, and parallel to, the pressures acting at the time they were formed.

[1] *Études synthétiques de géologie expérimentale*, 300–52.

[2] *Am. Geol.*, XII (1893), 368–75.

[3] *Trans. Am. Inst. Mining Engineers*, XXIV (1894), 130–38.

Instead of beeswax and resin, mixtures of paraffin and resin were used in the experiments. Several precautions were necessary in order to obtain good results. Paraffin alone faulted with a slickensided surface along a plane making an angle of 45° with the pressure, but no fine cracks appeared. The addition of a little resin, however, brought the desired cracks. The amount of resin used varied from just enough to stain the paraffin yellow to enough to give it a brown color. No good results were obtained with the material above a freezing temperature and the best results were had at about 0° F., or, rather, at the lowest temperatures available. Artificial cooling did not give such good effects as those obtained by allowing the material to harden by exposure to the air on the coldest winter days and subjecting it to pressure at the same temperature. The paraffin was cooled in tins and cut into convenient sizes while soft. It was found that the cracks came out better on the natural upper surface than on the smoother, glazed sides and bottom which had been in contact with the tin and better than on surfaces which had been planed smooth. This made it necessary to cool the paraffin carefully; otherwise, with its large contraction, the surface became badly wrinkled. It was also found best to cool the material rapidly and use it as soon as hard. The better results seemed to be connected with lack of uniformity in the material. Results were better on the less regular surfaces and on material so recently cooled that it probably was not equally hard throughout. Likewise, since it was cooled by being placed on snow with the upper surface exposed to the air, the rates of cooling of the upper and lower surfaces were different, with a consequent variation in grain through the mass. Daubrée was careful to have his blocks regular in shape, with faces planed smooth, and probably his material was nearly homogeneous. The experiments on paraffin showed that such care was more than wasted in preliminary experiments like these, where no attempt was made to use carefully regulated conditions for the purpose of obtaining mathematical results.

In size the blocks used were from two or three to eight or ten centimeters in length and breadth and from less than a centimeter to three centimeters in depth. These dimensions were employed in all combinations of long and narrow to square, thick, or thin.

The blocks were compressed in a small hand vise and one or two of the dimensions of the blocks were often greater than the corresponding dimensions of the jaws of the vise. Little attempt was made to smooth the paraffin to regular shape; therefore the application of the pressure was often very uneven. The varying conditions made it possible to trace cause and effect, and, since several scores of blocks were compressed and each showed different effects in its

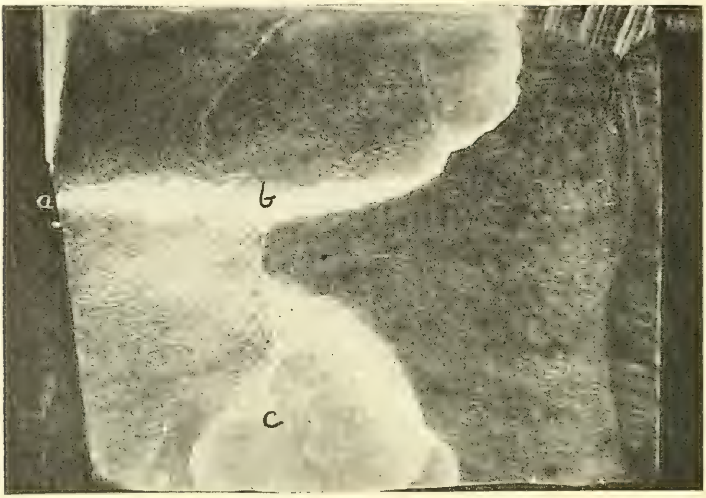

FIG. 9.—Photograph of a block of paraffin after compression. $\times 1.4$

different parts, the results may be taken as general for the given material and given conditions.

Figs. 9 and 10 are photographs of two of the blocks after they were compressed. The pressure was applied parallel to the plane of the paper in a line up and down the page. These blocks were hardly of average value for study but they were stained so dark with resin that it was possible to photograph the white cracks. Attempts to photograph the lighter-colored specimens by transmitted light were only partly successful. Fig. 11 is a composite showing the more common results of compression. The pressure was applied over the face *abcd* and the opposite face. Near the right edge is shown the result of a fairly even pressure over a rough face. With even pressure and a smooth face the material would

break and slip with a slickensided surface along a plane making an angle of 45° with the pressure, that is, a plane whose outcrop on the face *abef* made an angle of 45° with the edges and whose outcrop on *bdfg* was a straight line parallel to the right edge. On account of the uneven face some points usually received a greater thrust than others so that the material broke in sections, the outcrops on the flat faces being parts of ellipses as shown in the figure. These sections each moved along a slipping plane of about 45° with the pressure, so that where there were several rows of semi-ellipses

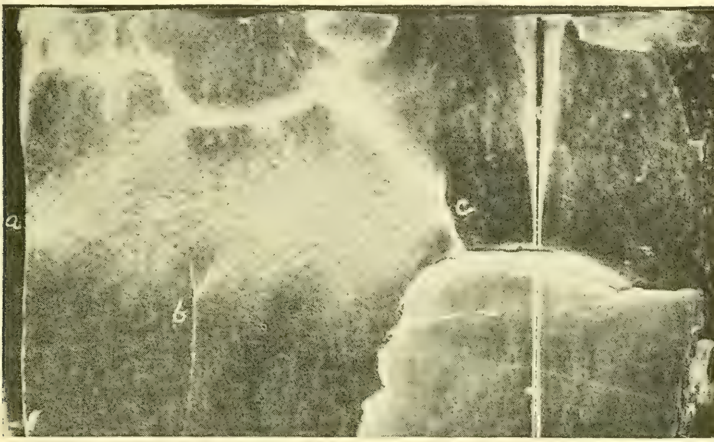

FIG. 10.—Photograph of a block of paraffin after compression. ×1.4

the material had been broken along several parallel slipping planes. The outcrop of the main slipping plane is shown from *h* to *i*. There was a similar tendency for the planes of slipping to break off the corners along the edges of the end faces. This is shown at *h* and *i* where the breaking plane extends farther in than it does near the center of the long edges. Sometimes this was carried so far that the point *h* was near the center of the shorter edges.

At the left edge is shown the result of a thrust which was stronger along the center of the face than near the edges *ac* and *bd*. In practice this occurred when the face of the material was wider than the jaws of the vise. The effect was usually to split the material in a nearly horizontal plane which, farther in, merged into a small slipping plane at 45° with the pressure with an outcrop along *jk*.

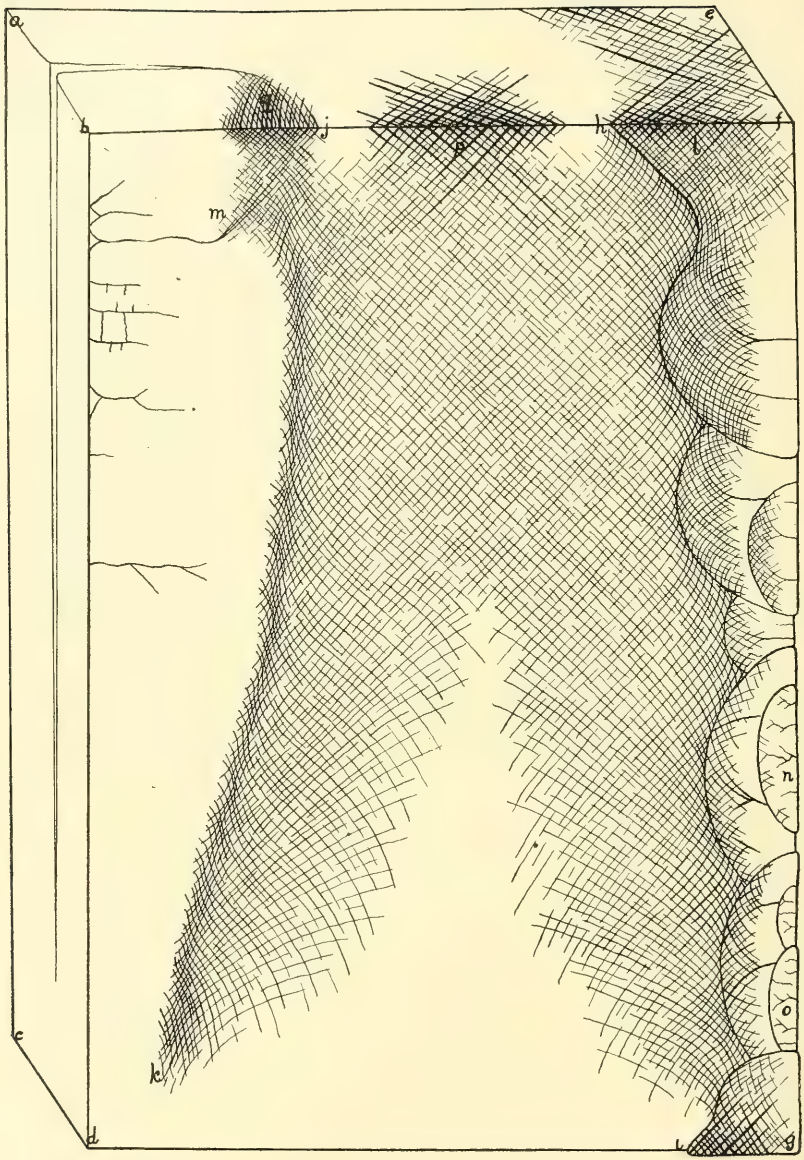

Fig. 11.—Composite showing the cracks produced by compression

Along *hi* slipping has taken place but *jk* represents the condition just before breaking at the surface. The outcrops of the slipping planes occurred on either the face *bfgd* or *aec* or both, depending upon the application of the pressure.

With the distance between the jaws of the vise small compared with the length and especially with hard material at the lowest temperatures, the blocks often broke in planes nearly parallel to the end faces *abef* and *cdg*. The break through the middle was nearly a plane face and the breaks toward the ends were convex outward, resembling a pile of thin cards compressed at the ends so that the cards bow out. In these breaks the faces separated instead of slipping on each other and slickensiding. With material cooled rapidly to a low temperature these faces were usually covered with even, featherlike markings which were of interest because they closely resembled the patterns which J. B. Woodworth[1] found on the faces of joint planes. The patterns consisted of a central smooth axis from which extended scales of the paraffin shaped like a half-crescent with the point toward the axis. The scales were free along the concave margin and passed into the material along the convex edge. The position of the axis of the feather depended on the application of the pressure and the homogeneity of the material but was usually near the middle of the breaking plane.

With similar hard material and the pressure applied to points as along *fg* the breaking took place along surfaces shaped much like half a bell with the rim in the face *bfdg*. These bell-shaped surfaces were also covered with half-crescent scales with their points toward the place where the thrust was applied and their broader portions radiating outward.

Such markings are associated with separation of faces rather than slickensiding. Further study of them might be of interest in connection with the question of whether joint faces are separated at some time in their formation or are always held tightly together. Such markings were not seen on the joint faces of the Ithaca region.

NETWORK OF CRACKS

Besides the large breaks, there was a system of intersecting even cracks similar to the fine network found by Daubrée. He compared

[1] *Proc. Boston Soc. Nat. Hist.*, XXVII (1896), 163–83.

them with joints. Their behavior under various conditions of pressure and breaking of the material is shown in Fig. 11 and the photographs.

Perhaps the most conspicuous result of the experiments on paraffin concerned the relation between these cracks and the forces at right angles to the active pressure. Whatever the direction of the cracks in the inner part of the block, whenever they approached the unconfined edges they turned so that their outcrops made angles of 45° with the edges. This is shown at *j*, *l*, and *i* in Fig. 11 and at *a* in Fig. 10. At *a* in Fig. 9 the same thing was present but the change occurred abruptly so near the edge that it did not show in the photograph. The cracks also turned or strengthened when they approached larger breaks as shown at *m* in Fig. 11, at *b* and *c* in Fig. 10, and from *b* to *c* in Fig. 9. Wherever these fine cracks approached free edges they immediately turned to the 45° position. In practically all cases the cracks became stronger near such edges as is shown in the photographs and indicated in the drawing.

Obviously, in rocks there would be few such places where the material acted on ended abruptly. In practically all cases deformation would be resisted by strong molecular forces at the sides and usually by the influence of overlying beds. Hence the cracks obtained by Daubrée and those at the edges and surfaces of the paraffin blocks could not be expected closely to imitate joints. More satisfactory results would be expected near the center of the block where the molecular forces would have a normal effect.

Near the edges there were often irregular cracks making small angles with the pressure like those shown at the left edge of Fig. 11. On the smaller semi-elliptic surfaces they were often forked, as at *n* and *o*, so that the portions of the break made equal angles with the line of pressure. Usually at some distance from the edge and beyond these irregular breaks the network of cracks appeared. They usually started at a fairly even distance from the edge, though often a few extended backward to the edge. At first they made oblique angles with each other, the line of pressure bisecting the acute angle. Soon they spread to right angles and then to larger angles near the outcrop of the slipping plane *hi*. There the line of pressure cut the obtuse angle. The cracks sometimes

became nearly perpendicular to the line of pressure and appeared as a mass of wavy lines as at *ab* in Fig. 9.

Where the application of the pressure split off part of the block as along the left edge of Fig. 11 the cracks usually started farther from the edge and omitted the acute-angled portion as along *jk* in Fig. 11 and *ab* in Fig. 9. Thus near the outcrop of the slipping planes these cracks were nearly parallel to the outcrop and were arranged symmetrically about the line of pressure.

The preceding are the forms of cracks which were most common but in the better specimens the central part of the block was usually covered with cracks and these were more regular than in the rupture portions of the paraffin. They occurred evenly over the large faces, commonly making angles of 90° with each other and 45° with the pressure. At their connection with the oblique-angled cracks near the slipping planes the angles changed rapidly. These cracks were usually stronger near the center of the end edges, as at *p* in Fig. 11, than at each side of the center. In the block shown in Fig. 10 the breaking lines corresponding with *jk* in Fig. 11 both occurred near the center so that the cracks across the center showed a compromise between the large angles near the breaking lines and the right angles of the unbroken center of a block.

In Fig. 11 is shown the effect of a greater thrust near one end of the block. This was commonly caused by a greater width of the block at one end. Where the thrust died out the cracks were not symmetrical about the general line of pressure. This is shown in the lower central part of Fig. 11. Sometimes locally, as near an irregular breaking edge, a few cracks would occur in nearly the shape of a fan, one set forming a few rays and the other set curving at right angles to the rays.

Since the diagonal cracks made angles of 45° with the edges of the end faces, the planes of the cracks near the ends were nearly parallel to the faces of an octahedron. The inclination of the cracks near the center of the block could not be determined, but in some cases where the oblique cracks continued to a point near the edge the outcrop on the end faces was less than 45° with the vertical, as shown at *q* in Fig. 11. Probably the inclination varied

as much from 45° as the direction did in the parts of the block away from the influence of the ends.

Fig. 11 shows the general appearance of the cracks with the exception that the lines were seldom sharp except near the edges. They were usually blurred by the crushing of the material, as shown in the photographs.

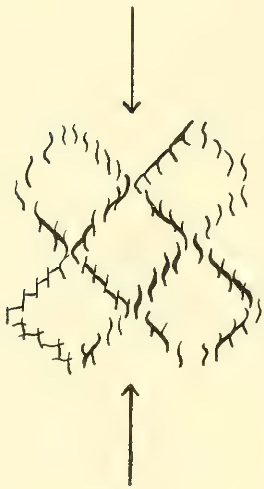

Fig. 12

Closer examination of some of the diagonal cracks on the upper faces showed that the lines were not continuous but consisted of a series of more or less sigmoid lines arranged in diagonal rows, as shown on an enlarged scale in Fig. 12. Sometimes the diagonals consisted of a series of steplike fine cracks, as shown in the lower left-hand corner. Evidently where the thrust was sufficient to cause rupture the breaking took place along the diagonals, but a lesser thrust left the series of smaller cracks which had been formed first. These cracks were usually a millimeter or two in length.

FINEST CRACKS

When the material was examined by transmitted light with a hand lens it was found that still other cracks were present. Over the upper surface were many lines like those shown enlarged in Fig. 13. They looked like rift in granite.[1] They were about a millimeter long and were fine and sharp. They occurred especially where the thrust was unusually strong, in front of the semi-elliptical breaks, though they were often present between the slipping plane and the face where the pressure was applied. They often

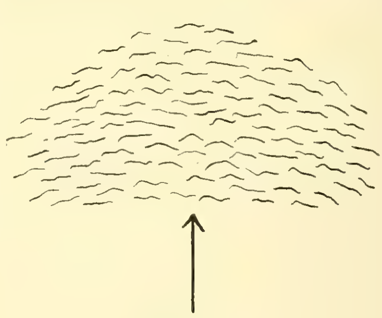

Fig. 13

[1] R. S. Tarr, *Am. Jour. Sci.*, 3d ser., XLI (1891), 267–72.

occurred in the same places as the larger diagonal cracks, so that the surface showed two sets of opaque 45° cracks with these fine, wavy lines superposed upon them over the whole surface and arranged nearly at right angles to the pressure. Where the thrust decreased laterally there was a suggestion of a change in direction which would make the average direction of the cracks slightly concave toward the thrust.

When the paraffin was pared down so that a section from the interior could be studied by transmitted light it was found that in sections several millimeters thick there were opaque diagonal lines, but these lines no longer made angles of 90° with each other and 45° with the pressure as at the surface. The angles between the two were usually about 70°, with the line of pressure bisecting the acute angle. These were commonest where the thrust was unusually strong.

When the paraffin was cut to a thickness of about a millimeter these opaque lines disappeared and the material was seen to be full of fine, sharp, wavy cracks about a millimeter long like those shown in Fig. 13 but parallel to the pressure. Examination with a hand lens did not show that they were arranged in diagonal rows, but, since it was found uniformly that a thicker section gave broad opaque lines and these lines disappeared entirely in a thin section and fine wavy lines appeared in their place, it seemed, from analogy with the sigmoid lines and diagonals of the upper surface, that the breaking within the mass of paraffin consisted of fine cracks nearly parallel to the pressure, the cracks arranged in diagonal series so that by superposition they gave opaque lines in a thick section.

Thus in passing from the unnatural surface conditions to the interior of the mass where conditions would be more similar to those in the rocks the angles between the larger lines decreased so that the lines made a smaller angle with the pressure and the smaller cracks of which each line was made became straighter and entirely separated from each other. Here was a set of cracks uniformly present within the mass subjected to pressure, the cracks each nearly parallel to the line of pressure and suggesting an arrangement in two sets with the pressure bisecting the acute angle.

Unfortunately the fine lines at right angles to the pressure

which were seen abundantly on the surface were not found within the mass, though certain fine lines may have been their representatives. If so, they were smaller than at the surface and too fine compared with the grain of the material itself to be studied with any accuracy. All of these finer cracks, both at right angles to, and parallel to, the pressure, could be studied only in thin sections by transmitted light and required a lens, but they were practically the same throughout the large number of specimens in which they were found, so that their general character was evident. The cracks were too fine for a determination of their inclination, but it probably was not large, since the cracks appeared as sharp lines instead of broad, opaque lines as would be the case if they ran diagonally through the material. Both of the sets of finer cracks appeared in the central unruptured portions of the paraffin as well as in the broken parts. The material appeared unbroken but when it was held before a light the places of greater thrust were found to be opaque, and examination with a lens showed the fine lines which caused the opaque appearance.

The experiments were carried about as far as possible under these conditions, since the most interesting cracks were too fine for study with the naked eye and the irregularities of the material were large compared with the size of the cracks. Further study should be made with finer-grained material which could be studied with a microscope, or the conditions should be such as to give larger cracks.

DEDUCTIONS

AGE OF THE JOINT PLANES

STRIKE JOINTS

It is apparent that the strike joints were formed in connection with the low folds of this region. Their average strike corresponds too closely with the axes of the folds to be accidental. If they had been formed before the folding with a uniform, nearly vertical inclination they would now be nearly at right angles to the bedding planes; that is, if the planes of the joints were produced they would meet below the axes of anticlines and above the axes of

synclines. The reverse was found to be true. If they originally made a uniform moderate or large angle with the vertical, folding would have increased the angle on one limb of the fold and decreased the angle or reversed it on the other. Thus angles such as were actually found might be produced on one limb of the fold but not on the other. If the joints had a varying hade which reversed near the axes of subsequent folds the present angles might be produced, but that is too improbable.

The joints might have been formed with uniform, nearly vertical inclination after the beginning of the folding. Subsequent subsidence of the folds would give the angles observed. This is not probable, because the faulting indicates that much of the movement took place after the formation of the joints. This theory would require a reversal of all the later folding and enough more to reverse the joints. It would not alter the question of the age of the joints, since, if their hades were produced in this way, they must have been formed during the folding.

The upper limit for the date of the jointing is set by the faulting. The nearly horizontal faults of this region uniformly displace the joints which they cross; therefore the joints were formed before the faulting, or at least before the end of the movement along the fault planes. These faults were presumably formed in the time of active folding here, that is, during the Appalachian Revolution. This sets the date of the joints as somewhere between the beginning of the pressure which caused the folds and the climax of the folding as indicated by the active faulting. Unless the joints were formed by subsidence of the folds their direction of inclination is, in most cases, the same now as when they were formed. The angles, however, have been altered by later folding and in some cases may have been reversed. This may explain some cases where the reversal of direction takes place at one side of the axis of a fold.

DIP JOINTS

The evidence for the dip joints is not so conclusive, since the lack of detailed knowledge of the pitch of the folds prevents a comparison of the variation of the hade of the joints with the variation of the folds. From what is known of the pitch the hade of

the dip joints seems to be mainly in the same direction as the pitch. At any rate, their hade is not such as would be produced by subsequent uplift of joints formed with uniform, nearly vertical inclination.

As in the case of the strike joints, the upper limit is set by the faulting. They cannot be older than upper Devonian, the age of the rocks in which they occur. One set of dip joints is nearly at right angles to the axes of the folds and the other set lies near the local resultant force acting during the folding as indicated by the strike of the faults. The angle between the two dip sets varies with the intensity and pitch of the folds. They are not so well differentiated near the weak Watkins anticline as near the strong and pitching Shurger Point fold and the strong Alpine anticline south of the Enfield syncline. The comparative strength of the two sets varies also. The experimental work showed that a variation in the forces at right angles to the active pressure had a large effect upon the cracks. The pitching of the folds and the large angle shown by the faults between the local resultant force and the general force at right angles to the axes of the folds indicate that the forces at right angles to the pressure varied considerably from place to place during the folding. Under such conditions the two dip sets would be expected to differ in strength and to vary with the folds if they were formed at that time.

The experiments showed that subjecting paraffin and resin to pressure gave fine cracks at right angles to the pressure and nearly parallel to the pressure. The latter were developed from a double set bisected by the line of pressure and might themselves form a double set if they could be measured carefully. During the Appalachian Revolution such a horizontal pressure was applied to the strata and should have formed cracks having directions like the observed joint planes. It has not been shown that there was enough disturbance of this region between the time of deposit of the rocks and the formation of the folds to have produced joints. If that were the case two independent groups of strike and dip joints should be found, for experimentally both strike and dip cracks were formed by a single application of pressure. There are two sets of dip joints found but they seem to be too closely

connected to have been formed by entirely separate forces and the strike joints distinctly belong to a single set.

It has sometimes been assumed that joints at right angles to each other were formed at separate times, the forces producing the second set being at right angles to the forces producing the first set, that is, both sets bore the same relation to the forces which caused them but the forces were in different directions the two times. Opposed to this is the fact that the strike and dip joints are not similar. If a certain set of forces produced the strike joints, then a similar set of forces acting at right angles to the former forces should give another set much like the strike joints except in direction. This is not the case in the Ithaca region. Experimentally cracks were produced in all the required directions during the same application of pressure and it does not seem necessary to assume that strike and dip joints were formed by separate applications of pressure in the rocks.

In most cases the master joints are sharply cut by the faults but in some cases there is evidence that some strain existed along the fault planes at the time the joints were produced. Near the right in Fig. 1 is a dip joint which is strong and normal excepting near the fault line where it abruptly breaks into a fanlike set of radial small cracks with the point below. This fan is about a foot across and the fault crosses its center. Above the fan the joint becomes normal again. Evidently when the joint was formed there was some strain at the place where movement occurred later or perhaps the faulting had already begun. Many of these fanlike irregular joints were seen near faults and were evidently due to strain at the fault planes, but the others were not examined for their relation to the master joints. Investigation would probably show that more of these are connected with the master joints and in the case described the fan is certainly a part of an otherwise normal joint belonging to one of the dip sets.

The evidence thus indicates that all the master joints were formed in the earlier part of the period of folding. Probably when the pressure reached a certain value, less than its maximum, the joints were formed rather abruptly. Further pressure caused faulting, or perhaps some faulting occurred before the formation

of joints and the continued pressure caused further slipping which displaced the joints. It is not necessary to assume that the strike and dip joints were formed at exactly the same time. They are unlike in other respects and may have been in this. In the experiments the fine cracks could not be watched as they were formed so that their time relation was not determined.

EVIDENCE OF THE DIKES

All the known dikes of this region are in the dip joints. None are found in the strike set. Kindle[1] has suggested that the dip joints were older than the Appalachian uplift and the igneous matter was intruded before the formation of the strike set. Another suggestion that has been made assumes that the faces of the strike joints were held tightly together by pressure so that the dike material could not force its way in. Opposed to this is the fact that many of the dike streamers are exceedingly thin, penetrating fine breaks.

The dikes are mostly in the Portage rocks and in these the dip joints are usually the stronger. Judging from the experiments the faces of strike joints would be held together but under some conditions there might be a tendency for the faces of the dip joints to separate. This would allow the igneous matter to enter the dip joints more easily. Perhaps the dip joints antedate the strike set, even though both were formed during the folding. Since the dikes are faulted, they were obviously formed between the time of the dip joints and the climax of the faulting. Further study of the relations between dikes, joints, and faults would probably be useful in determining the exact order of formation of the various sets of joints, but from the present evidence it does not seem necessary to assume that the dip sets were present before the Appalachian Revolution in order to explain the dikes.

The time of formation of the minor joints is not so evident. Probably most of them were formed at about the same time as the master joints. Along the walls of the dikes the rocks are cut by innumerable small jointlike cracks which were evidently formed as a result of the pressure of the dike material.

[1] *Folio 169*, p. 13; field edition, pp. 96–97.

The Ithaca region seems particularly favorable for the study of joint planes. The stratigraphy is comparatively simple, showing only one time of crustal movements sufficiently great to be accompanied by jointing. The pressure was strong enough to produce joints and folds and faults with which the joints could be compared, but it did not carry the folding far enough entirely to reverse the joints and so complicate the record. In regions of higher folds the hades of the joints should be studied with the plane of bedding rather than the horizontal as a datum plane.

CAUSE OF THE JOINT PLANES

Geologists are not agreed upon the cause of joint planes in stratified rocks. On account of the observed relation between joints and the strike and dip of rocks it is usually conceded that they are connected with movements of the earth's crust. Some of the theories of the cause of joints have been abandoned. Among those still recognized are tension, earthquake shock, torsion, and shear.

TENSION THEORY

According to the tension hypothesis joints are formed during folding. As the folds develop there is tension along the upper surface of anticlines and the under side of synclines. The rocks then crack in planes whose outcrops are parallel to the axes of the folds. At right angles to the axes the pitch of the folds causes another set, the dip joints. A general objection to this theory is the character of the joint faces. They are smooth and are remarkable for passing directly through hard masses like pebbles or concretions, instead of around them. The Hamilton shales of this region show this very well. The rock is mostly an even shale but there are several bands of hard concretions. Some of the joints do not pass through the concretions but probably the majority cut them in a smooth plane even with the rest of the joint face. It does not seem probable that a crack due to tension and separation of faces would pass so smoothly through concretions instead of around them. The general smoothness of a joint face in shale is very unlike the surface caused by breaking rock apart.

Joints formed by tension would be arranged radially about

the folds, that is, if their planes were produced they would meet below the axes of anticlines and above the axes of synclines. The reverse was found to be true. It seems difficult to explain the hade of the strike joints by the tension theory. Neither does this theory account for the double nature of the dip joints nor for the mass of minor joints in all directions. The perfection of jointing in some parts of this region is out of proportion to the amount of cracking necessary to relieve the tension in such low folds.

EARTHQUAKE THEORY

W. O. Crosby[1] offered an earthquake hypothesis as an explanation of joints. Later[2] he emphasized the effect of shock on rocks already under strain rather than shock alone. Crosby stated some of the more important objections to the formation of joints by earthquake shock alone. Such breaks would not become approximately vertical for some distance from the epicentrum and then the energy of the shock would be largely dissipated. In the Ithaca region the inclination of the master joints is nearly vertical and in changing from one side to the other passes through the vertical, not through the horizontal as would be expected from earthquake waves. In order to explain the commonly observed right-angled relation of joints, it has been assumed that after one shock had produced a set in one direction a large component of a subsequent shock would be relieved by slipping along the already existing planes, unless it was at right angles to the earlier shock, except in case of very rapid vibrations. Only one set of planes would be formed by each shock. The direction of the strike joints might be accounted for by making the focus of the earthquake a long fault parallel to the axis of the fold. An objection to the earthquake hypothesis apparent in this region is the symmetry between the joints and folds. It is not probable that the folds would influence cracks due to earthquakes to such an extent nor is it probable that separate shocks occurred simultaneously in the different folds to cause a reversal of the joints near each axis.

The earthquake theory alone seems awkward, since it requires

[1] *Proc. Boston Soc. Nat. Hist.*, XXII (1882), 72–85; XXIII, 243–48.

[2] *Am. Geol.*, XII (1893), 368–75.

an improbable system of separate shocks to account for the several sets of major joints and the mass of minor joints. These shocks must have been symmetrical with the forces producing folding, and the resulting breaks were of different character at different times. It seems simpler to refer the joints mainly to the orogenic forces, but perhaps as in Crosby's combination of shock and torsion the shock attending crustal movements materially affects the formation of cracks in strained rocks.

TORSION THEORY

In Daubrée's torsion experiments the material broke in two sets of cracks, making angles of 90° with each other and 45° with the axis of torsion on the large faces of the plates. The inclination as shown on the narrow side faces was as high as 50° with the vertical, though usually less. Becker repeated these experiments with plates of glass of various dimensions. He obtained the same directions of outcrop on the large faces as were found by Daubrée and he also found that the breaking surfaces were curved. Sometimes the outcrop on one of the large parallel faces of the glass was straight and on the other S-shaped.

Many of the minor joints of the Ithaca region are shaped like the surfaces Becker obtained by torsion and they are probably due to this cause. The most important of the curving joints are those which strike north of west. The well-developed joints of large hade found near the Shurger Point fold also resemble breaks due to torsion. The innumerable small joint faces are probably due to local twisting.

The master joints do not show such curvature in a single exposure, though perhaps if their full extent were seen they would be found to have a twisted surface. The torsion theory has been criticized because the breaks make angles of 45° with the axis of torsion while joint planes are nearly parallel to the dip and strike of rocks. If the ends of a piece of cardboard are twisted in opposite directions the resulting ridge runs diagonally between the corners or nearly parallel to one of the sets of cracks obtained by Daubrée. In order to twist the plates, however, Daubrée applied a couple at right angles to the plane of the large faces. In the rocks this

would correspond with a set of vertical forces. The pressure forming the folds of this region was tangential to the beds rather than vertical; therefore the conditions in the rocks were unlike the conditions of the torsion experiments, though there was probably some variation in the vertical forces. Moreover, in comparing the various theories for the formation of joints it may be considered that torsion like that employed by Daubrée is only a special case of shear.

SHEAR THEORY

Daubrée also obtained a network of cracks by a compression which caused shearing stresses. Becker[1] has given a mathematical treatment of strains in rocks and explains joints as the result of shear. The field observations show an intimate relation between the master joints and the forces which caused the folding. Those forces are supposed to have been tangential to the beds. The symmetry of the faults in the encrinal limestone about a nearly horizontal plane is evidence that, if not vertical, the chief forces were nearly horizontal. By applying pressure to the narrow faces of blocks of paraffin fine cracks were obtained which bore nearly the same relation to the pressure which the joint planes bear to the pressure active during the folding. The pressure used in the experiments corresponded with a tangential pressure on the strata. The evidence points toward the formation of the joints as the result of a nearly horizontal pressure, but in the present state of knowledge of the relations between stress and strain in rocks the relations between joints and the strains caused by this pressure are uncertain. Strains in rocks are exceedingly complicated, since the forces vary and the materials acted upon are not homogeneous.

The joints found here do not exactly agree with the breaks discussed by Becker. They are similar in some respects but unlike in others. He concluded that faults, joints, and slaty cleavage all lie in the planes of maximum tangential strain. This implies that joints are only faults of little throw. The faults in this region were apparently formed under the same set of forces as the joint planes; yet the two are very unlike. Of three planes at right angles to each other, the faults lie approximately in one, the horizontal, and the strike and dip joints lie approximately in the other two, the

[1] *Bull. Geol. Soc. Am.*, IV (1893), 13–90; *Proc. Wash. Acad. Sci.*, VII (1905), 267–75; *Eng. and Mining Jour.*, LXXIX (1905), 1182–84.

vertical planes. Slipping may occur in two planes which have the same strike. In the encrinal limestone both these slipping planes are represented by true faults.

If there was differential movement of the joint faces during the folding, that throw was not more than a fraction of an inch. On the other hand, there was displacement of half a foot along the fault planes after the formation of the joints. If joints lie in the planes where slipping would be expected to occur, it seems strange that under forces strong enough to cause noticeable displacement along known faults there was little or no movement along the joints if the latter are incipient faults. In the actual case found in this region the joints are so nearly at right angles to the horizontal faults that the force along the fault planes had almost no component along the joint planes, hence movement along the faults could take place without slipping along the joints even though they formed planes of weakness. If pressure is applied to the rocks at an oblique angle with the joint planes after the joints are once formed, slipping would be likely to result; but such subsequent movements are not an essential part of the production of the joints.

One of the difficulties in explaining joints by pressure theories has been the presence of a set of joints apparently parallel to the pressure. The Ithaca region shows that here, at least, the dip joints really consist of two sets not parallel to the pressure but more or less symmetrically arranged about the pressure and making a small angle with it.

If the faults lie in the true slipping planes then the small hades of the joints are still unexplained. Perhaps they are due to shock associated with the strains due to the pressure. The conditions under which the joints were formed probably included translation, rotation, compression, pure shear, some torsion of the kind employed by Daubrée, and shock. To determine the exact manner of formation of joints and their relations to stresses, there is need of detailed field observations on the relations between joints and the forces producing them, as indicated by attendant faults and the axes and pitch of folds, and need of experimental work by which cracks resembling joints can be produced under such conditions that measurements may be made to determine the relations between stress and strain.

Reviews

The Geology of the Lake Superior Region. By Charles Richard Van Hise and Charles Kenneth Leith. United States Geological Survey, Monograph LII. Pp. 641; Figs. 76; Pls. 49.

All geologists interested in pre-Cambrian geology will view with pleasure the appearance of this monograph. While the work is to a considerable extent a compilation of all other important publications on this region it contains much which is new and a great deal of information, especially on the origin of the iron ores, which here appears in print for the first time. The geography, general geology, bibliography, and history of the economic development of the region are discussed in a general way. These discussions are followed by detailed descriptions of the geology of the various ore-bearing districts, the geological series, the glacial geology, the origin of the ores of iron and copper, a genetic classification of the iron ores of the world, and finally by a summary of the geological history of the region with special mention of the unconformities separating the different series.

The region covers an area of approximately 181,000 square miles of which the copper and the ten great iron-bearing districts combined make less than 3 per cent of the total. The relief varies from a maximum elevation of 2,230 feet above sea-level in Minnesota to a minimum of 376 feet below sea-level in the basin of Lake Superior.

In the section on physical geography, edited by Lawrence Martin, it is concluded from a discussion of the peneplaination of the area that the region was base-leveled in pre-Cambrian time. While the subject is treated from nearly all standpoints and the matter presented is good the reader feels that although such a statement as, "Earlier possible peneplain levels—in the Huronian for example—would have been warped or folded by pre-Algonkian deformation," appearing on p. 88, must be assigned to an oversight or a typographical error, great difficulty is experienced in distinguishing between statements which refer to the present peneplain and those which refer to the plain which was doubtless formed in the early Algonkian. Observations are made regarding the origin of the Lake Superior basin and the conclusion reached that it is largely due to graben faulting and glacial erosion.

Much new data relating to the iron ores has been collected, especially regarding their chemical composition, porosity, and moisture content, and the results have been depicted graphically on the triangular diagram which is so frequently employed in this work. It is shown that the phosphorous in the ore of the Mesabi district has come chiefly from the overlying Cretaceous rocks while in the Penokee-Gogebic district the phosphorous content of the ore increases with the percentage of iron indicating that this element was originally in the ore. In the vicinity of dikes the phosphorous content is high and leached dikes show a loss of this element so the igneous rocks appear to be the original source of it. No definite phosphorous minerals have been found, but the association of calcium and phosphorous in some of the deposits suggests the presence of apatite.

The average analysis of ore from the Mesabi district for three years shows a decrease from 60.70 per cent to 58.83 per cent in iron and a corresponding increase in phosphorous.

In the description of the Marquette district, peridotite as well as syenite is considered of Laurentian age and this fact is of interest since we have become so accustomed to thinking of this series as acid in composition. Regarding the placing of slates under the Ely Greenstone, as is done on p. 119, the question might be raised, whether it would not be better to reserve the term greenstone for lithological characters and apply it only to chemically and mineralogically altered, basic, igneous rocks.

The Keweenawan series is regarded as largely terrestrial in origin and a number of excellent reasons are given for drawing this conclusion. A few of these are: the thickness of the sediments and the frequent repetition of conglomerate beds; the feldspathic, poorly assorted and almost completely oxidized character of the sediments; the frequent occurrence of ripple-marks and mud-cracks, and the fact that the matrix of the basal conglomerate on the north shore is frequently limestone in such a condition as to suggest subaerial deposition similar to that occurring in the Bighorn Mountains at the present day.

The origin of the Keweenawan igneous rocks is assigned to fissure eruptions in the vicinity of the Lake Superior basin caused by orogenic movements and the down-warping of the basin apparently began in the Middle Keweenawan epoch. The source of the sediments is found chiefly in the underlying igneous rocks and the maximum thickness of the series is regarded as not more than half of that which was assigned to these rocks by some earlier writers. The discrepancy is due to the consideration that they were deposited on an inclined surface.

In the classification of the Keweenawan igneous rocks, p. 396, by A. N. Winchell, the term plagioclasite is used as a synonym for anorthosite. While this term is not so euphonious as anorthosite and might include rocks of greater range in chemical composition than that usually designated by this term it has simplicity and the advantage of corresponding in use to the terms amphibolite, pyroxenite, and leucitite.

The Lake Superior sandstone is for various reasons assigned to the Cambrian.

Beginning with chap. xvii the iron ores are discussed in great detail. The deposits are divided, chiefly on a genetic basis, into the pre-Cambrian sedimentary types, the source of nearly all the ore; titaniferous magnetites constituting magmatic segregations in gabbros; magnetic ores representing pegmatite intrusions in basic rocks; residual bog ores of Paleozoic age; and hematites from the Clinton series. The average iron content of all the original phases of the pre-Cambrian iron-bearing formations, not including the slates, is 24.8 per cent and the average for the ferruginous schists and jaspers is 26.33 per cent. If the average be taken for the formations including the ores the content of iron is 38 per cent showing the influence of concentration.

About $21,600,000 has been spent in diamond drilling in the region at an average cost of about $3. per foot. The average cost of mining underground is probably about $1. per ton, and the cost of transporting ore to the furnaces (in 1907) about $2.14 per ton. The stripping operations in the Mesabi district annually exceed in extent those on the Panama Canal.

The estimated reserves of pre-Cambrian ores is placed at 1,905,000,000 long tons.

The genesis of the sedimentary iron formations is the topic of greatest interest in this monograph and it is interesting to see the change of view by the senior author. He has to a large degree forsaken his earlier views which held that the iron deposits were principally the products of rock weathering for those which consider these deposits as coming chiefly either directly or indirectly from igneous rocks without the action of ordinary weathering agencies. The fact that anyone so familiar with these deposits as President Van Hise should adopt the new theory is a strong point in its favor. The hypothesis now accepted by the authors for the origin of the deposits is, briefly, that they are principally chemical sediments, that the original minerals were largely iron carbonate and silicate with some ferric oxides. The greater portion of the ore owes its present condition to secondary enrichment under special

topographical and structural conditions although a smaller portion may have been laid down originally with practically the present content of iron. The materials forming the schist, iron carbonate, and silicate are supposed to have been derived principally from basic igneous rocks either as magmatic solutions poured into the sea or from solutions of iron salts in sea water formed by the action of hot igneous rocks coming in contact with the salt water. Some of the iron was derived from these basic rocks by weathering and transported to delta deposits while other portions were deposited in bogs and lagoons through the action of plant life as bog ore is deposited at the present time. This bog and lagoon origin is assigned to the lenses of carbonate in carbonaceous slates and shales which appear to be delta deposits but the conclusions of Weidman that the Baraboo and much of the Lake Superior deposits are of this origin are not accepted. A pegmatitic origin is suggested for a portion of the iron and silica and some good evidence is presented from the Vermilion district in support of this view. A great deal of evidence is also presented to show that the ellipsoidal character of the greenstones is due to extrusion under water but on account of conflicting evidence, which has been impartially presented, it is felt that the case has not been made definite. It is argued further from the results of a large amount of data collected that ordinary weathering conditions could not produce such great deposits of chemical sediments without more clastic materials because there is not sufficient iron in the surface rocks nor adequate agencies to transport the iron to the site of deposition. These arguments are supported by a set of laboratory experiments which show that the very conditions postulated for the field can be produced in the chemical laboratory.

In these experiments it was shown that if hot Keewatin basalt be sprayed with salt water, a water-glass glaze is formed and if this water-glass be neutralized by hydrochloric acid, silicic acid and sodium chloride are produced. If the solution then be boiled it becomes alkaline. Thus is demonstrated a source for the alkaline silicates and when ferrous chloride and sodium silicate react, iron silicate (greenalite) and sodium chloride are formed. If iron silicate be attacked by carbon dioxide there is produced iron carbonate and silica. Further, if silicic acid be boiled with iron carbonate, greenalite is formed. These and many other experiments demonstrate the possible source of the material for the building up of the greenalite, siderite, and cherty deposits. Of particular interest is the statement that the precipitates of these substances show a distinct tendency toward banding.

The theory of origin as outlined in this work is the most complete exposition of the subject yet presented and it would be unreasonable to doubt, in the presence of the facts presented, the probability of the origin of a great deal of iron by its direct extraction from the igneous rocks in the manner above stated. The description of the possible origin of the banding in the jaspers is without doubt the best solution of the problem yet offered, as this feature of the deposits has always been a very difficult one to explain by any other theory. However, while it is not the purpose of this review to offer a better theory for the origin of these deposits, it might be remarked that while the authors have been fair and impartial in the presentation of this theory, which is largely new but still embodying some of the principles of one of H. N. Winchell's earlier hypotheses, there are a number of arguments which will not be accepted by those who hold that the weathering of rocks is the most important feature in the development of these deposits. It may be felt that sufficient importance has not been attached to the influence of physiographic conditions during the weathering processes, because bog deposits are developed under special topographic conditions, and the fact that so little iron was deposited in the Lower Huronian might be explained by the fact that during the early part of the epoch the relief was great and coarse clastic sediment was being deposited rapidly at the expense of the finer chemical sediments. Could not the fact that the percentage of iron in the iron formation is so large, compared with the amount of the clastics, be explained by selective transportation by which the chemical sediments were carried to lower ground and the clastics left to a greater degree on the higher levels? In the folding which followed the lower would be folded down and preserved in the synclines. Nor is the possible source of iron in the Huronian by the destruction of Keewatin iron deposits given sufficient prominence, as the amount of these rocks destroyed must have been very great. While there is comparatively little clastic sediment in the Keewatin of the Vermilion range there is much feldspathic, poorly assorted material in many other areas of iron-formation, which the authors regard as Keewatin, and which are in all other respects very similar to the Vermilion area. As to the question why there is not much iron in the great sedimentary series of the Paleozoic, which have been produced under normal weathering conditions, it may be replied that there are large deposits, without associated igneous rocks, in the Clinton series and Pennsylvanian system, both of which followed a period of extensive deposition of clastics, which represented probably subaerial conditions

and the destruction of great quantities of pre-Cambrian rocks. Although these deposits do not compare with those of the Huronian and Keewatin in extent, there never has been a period in the earth's history when such areas of fresh igneous rock in such a condition for rapid disintegration were exposed to weathering processes, nor have there been more favorable physiographic conditions for deposition than in Keewatin time. Regarding the relation of the iron-formation to different types of sediments it may be shown that the normal relation of bog deposits to clastic sediments today is that here they lie on sand and there on clay.

The origin of the copper ores of the Keweenawan is assigned chiefly to solutions of magmatic waters and to a lesser extent to the leaching of the igneous and sedimentary rocks by thermal waters. While this view is not entirely new it is much better established here than ever before by the application to the problem of rock alteration, the knowledge now possessed of the difference between the results of alteration by thermal solutions and by ordinary weathering processes. The presence of considerable chlorine in the deep-mine waters and the general scarcity of sulphides suggest that the chloride of copper was the principal compound in which the copper was originally transported. The copper was then brought to the metallic condition through the influence of ferrous compounds. The decreasing copper content of the deposits with depth is assigned to the nature of original deposition and not to secondary enrichment, as very little of the native copper is dissolved and transported.

The silver deposits on the north shore of Lake Superior are also regarded as having their origin in the Keweenawan, basic, intrusive rocks, and it is shown that chlorine is present to a marked extent in the deep-mine waters. From observations of certain similarities in geological characters it is therefore concluded that the Keweenawan copper, the Silver Islet silver, the Bruce Mines copper, the Sudbury nickel, and the Cobalt silver deposits are portions of a great metallographic province.

In a brief account of the Paleozoic rocks on p. 615, the term Proterozoic is introduced and made to include the Archean as well as the four members of the Algonkian group. This is not the sense in which the term has been used by other geologists and we surely have enough geological terms with two or more meanings. The author's use is a pointed illustration of the unsatisfactory usage which led to the adoption of the term Proterozoic, that is the illogical practice of including under a term of inferior rank the four great systems, Keweenawan, Upper Huronian (Animikie), Middle Huronian, and Lower Huronian,

as well as the unknown deposits represented by the great unconformities that lie between these. The use of Proterozoic for these four systems as a group implies that taken together they are regarded as similar in importance to the Paleozoic, Mesozoic, and Cenozoic groups. To include the still greater Archean series, with its unknown extension downward, under the term Proterozoic is to introduce a usage more unfortunate than that which preceded the adoption of the term Proterozoic. The authors of this monograph have always stood for a sharp line of demarkation between the Archean and other rocks of the pre-Cambrian. It would have been easy to have said Proterozoic and Archean and thus to have given to the group included under the name Algonkian the dignity to which it is thought to be entitled by those who use the term Proterozoic for it.

In the account of the great unconformity between the Upper Huronian and underlying rocks, given on p. 619, those who have held that the term Animikie should be applied to this as a distinct system, separated from the Huronian, will find much to justify their views.

In conclusion I would state that this monograph, aside from a few points mentioned, is logically arranged and very clearly written and, considering the number, variety, and excellence of the illustrations and having regard for the amount of detailed work, the results of which are here given, it must be considered as one of the finest publications of the Geological Survey.

E. S. Moore

"Versuche über Umkristallisation von Gesteinen im festen Zustande." Von F. Leewinson Lessing. *Centralblatt für Min., etc.*, No. 19, (October 1, 1911), pp. 607–14. Figs 7.

The experiments were planned to test the validity of the assumption that certain schists and contact metamorphic rocks have developed through the recrystallization of solid phases of previously existing rocks. A hand specimen of dunite and another of pyroxenite were subjected to a temperature of from 1,200 to 1,300° for nine months without showing signs of melting. The observed changes were textural, mineralogical, and chemical. The pyroxenite became a porous, coarse-grained aggregate of yellow, monoclinic pyroxenes spotted with ferric oxide grains. The olivine of the original rock had completely disappeared. The dunite was changed from an aggregate of angular and rounded colorless olivine grains interspersed with bunches of serpentine to a rock in which no serpentine was visible, but in its place were groupings of colorless

grains of an undetermined mineral, probably orthorhombic pyroxene. The olivine had become closely compacted and the grains jagged in outline, with numerous inclusions of dark grains, probably iron oxide. Analyses of the fresh and altered rock showed that the recrystallization involved oxidation and dehydration.

E. Steidtmann

Geology of the Thousand Islands Region. By H. P. Cushing, H. L. Fairchild, R. Ruedemann, and C. H. Smyth, Jr. New York State Museum Bulletin 145. Albany, 1910. Pp. 194; Figs. 14; Pls. 63; Maps 5.

The Thousand Islands region embraces the Alexandria Bay, Cape Vincent, Clayton, Grindstone, and Theresa quadrangles of northern New York. It is a district of pre-Cambrian, Cambrian, and Lower Silurian rocks and Pleistocene deposits, which are described and faunas and structures of which are discussed.

From facts gathered outside of this district the formerly called "passage beds" lying between the Potsdam and the overlying Beekmantown have been separated into two formations, the Theresa of the Upper Cambrian and the Tribes Hill of Beekmantown age. Although the unconformity that causes the separation has not as yet been detected in this region, the paleontological evidence indicates that the separation should be made. Of special interest is the new Pamelia formation, here first differentiated, which represents an arm of the Upper Stones River sea when that sea had encroached farthest to the northeast. No deposits of the Stones River sea have previously been known to occur in New York. The Pamelia basin was entirely separated from that of the Chazy, but is considered to be contemporaneous with the interval between the Middle and Upper Chazy. The term "Black River" as applied to Lower Silurian formations, has been redefined to include, besides the "Seven foot tier" of Hall, now renamed the Watertown limestone, the Lowville formation of which the upper part (the "cherty beds") is called the Leray limestone member.

The Pleistocene deposits consist of three kinds; those formed by glaciers, those formed in the glacial Lake Iroquois, and the deposits in Gilbert Gulf, an arm of the Atlantic after Lake Iroquois had been drained to sea-level.

The pre-glacial course of Black River has a new interpretation which states it to have been the headwaters of the St. Lawrence drainage instead of the Ontario valley.

The petrography of the pre-Cambrian rocks is discussed, and numerous analyses of granites, syenites, gneisses, and amphibolites are given.

A. E. F.

An Excursion to the Yosemite (California), or Studies in the Formation of Alpine Cirques, "Steps," and Valley "Treads." By E. C. Andrews. Jour. and Proc. of the Royal Society of N. S. Wales, XLIV, 262–315; Figs. 17.

Considerable space is given to *The Psychological Factor in the History of the Glacial Controversy* in which is emphasized the necessity of interpreting glacial features by the ice floods that formed them, and not by the present dwarfed representatives of those floods. The dynamics of ice stream erosion is discussed with special emphasis on the effects of ice falls and their recession forming "steps" and "treads," and on the formation of cirques and *roches moutonnées*.

Previous to glacial times, the Merced and Tenaya rivers had a fairly even descent through the Yosemite region, with a notable constriction in the valley between El Capitan and the Cathedral rocks. Later, with the ice moving through this constriction, the velocity at this point was increased, and, likewise, the erosive power, which developed a "step" with "basined tread." The "step" and "tread," once formed, were rapidly enlarged by recession through the processes of sapping and quarrying, and in their recession left hanging valleys, now marked by water falls.

A. E. F.

Department of Terrestrial Magnetism of the Carnegie Institution of Washington, Annual Report of the Director. By L. A. Bauer. Year Book No. 9, pp. 195–204; Pl. 1.

In a general summary is given the work done with the "Carnegie" in correcting magnetic charts, and an outline of her present circumnavigation cruise. The field work in the various countries, the ocean work of the "Carnegie," the office work, and the shopwork accomplished during the year are stated briefly. The map (Pl. 5) accompanying the report shows the status of the magnetic work accomplished both on land and sea up to October 31, 1910, and the uncompleted portion of the present cruise of the "Carnegie."

A. E. F.

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AUSTRALIAN GLACIATIONS

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The occurrence of a wide range of climatic conditions within the same latitudes during successive geological periods, is probably better illustrated on the Australian continent than on any other portion of the earth's surface. In Australia there have been three well-defined periods of glaciation, separated from each other by great intervals of time—Cambrian, Permo-Carboniferous, and Pleistocene. In each case the evidences of ice action are of considerable extent, all the distinctive features usual to areas that have undergone glaciation are unmistakably present, and in many instances the features are so clear and typical that it is difficult to realize the remote age of the ice marks. The purpose of the present paper is to give a brief summary of the main features of these extinct glacial fields of Australia.

CAMBRIAN GLACIATION

The Cambrian system is more fully developed in the state of South Australia than in any other part of the Australian continent, and forms the highlands running north and south from Kangaroo Island to Lake Eyre. A geosyncline was formed at the beginning of the Cambrian period, by the sinking of the old pre-Cambrian

floor below sea level. Then sedimentation followed, and there was laid down a great series of beds that reached forty or fifty thousand feet in thickness.

The upper members of the series are characterized by purple sandstones and slates, quartzites, and numerous limestones, the whole being, typically, of a dark chocolate or purple color. Some of the limestones are highly fossiliferous, and contain, among others, representatives of the following genera: *Olenellus*, *Ptychoparia*, *Dolichometopus*, *Microdiscus*, *Leperditia*, *Stenotheca*, *Ophileta*, *Platyceras*, *Hyolithes*, *Salterella*, *Ambonychia*, *Obolella*, *Orthis*, *Orthisina*, *Hyalostelia*, *Girvanella*. A limestone, near the upper limits of the series, consists almost entirely of *Archaeocyathae*, forming a "coral" reef 200 feet in thickness.

The lower members, beginning with the Brighton limestone, near Adelaide, show the following succession in descending order: Brighton limestone, Tapley's Hill ribbon-slates, Glacial till, Glen Osmond slates and quartzites, Upper phyllites, Black Hill (thick) quartzite, Lower phyllites, River Torrens limestone, Basal grits and conglomerates resting unconformably on a pre-Cambrian complex. The lower Cambrian beds are apparently destitute of organic remains, except for a few obscure traces of Radiolaria in the siliceous limestones.

From the above order of succession the stratigraphical position of the glacial deposits is perfectly clear, and from their superior hardness, and association with an underlying quartzite, they form parallel ridges, being repeatedly brought to the surface by synclinal and anticlinal folds. The beds extend from near the south coast, for several hundreds of miles northward into the interior, having been traced as far north as Hergott ($29\frac{1}{2}°$ S. lat.); and in an east-and-west direction, from Port Augusta, at the head of Spencer Gulf, eastward to the Barrier ranges in New South Wales, a distance of 200 miles.

Throughout this great extent of country the glacial beds preserve a remarkably uniform character. They attain a thickness of 1,500 feet, and for the most part consist of a bowlder clay or till, having a mudstone base which is gritty, and carries stones, irregularly disposed and of all sizes, up to 9 feet in diameter. The bowlder

clay sometimes passes into a coarse, angular grit in irregular masses; or includes sandstones, slates, and thin gritty limestones.

The included stones are of the nature of erratics, being foreign to the localities in which they occur. They exhibit a great variety of types, such as granites, gneisses, and other granitoid rocks,

FIG. 1.—Cambrian glacial till (showing erratics of granite, gneiss, quartzite, etc.). Sturt Valley, S. Aus. *J. Greenlees, photo.*

quartzites, porphyrites, schists, etc., some of which cannot be referred to any locality within the limits of South Australia (see Fig. 1).

The very close resemblance which this ancient till bears to ice deposits of a recent date is at once recognized by the experienced observer, but the glacial origin of the beds was not taken as proved

until the discovery of subangular erratics, faceted and ice-scratched, placed the question beyond doubt. These glaciated stones are not at all uncommon, and can be obtained from most of the outcrops of the till (see Figs. 2 and 3).

The Lower Cambrian of South Australia has, in many places been subjected to considerable pressure and deformation. These diastrophic movements have affected the glacial beds in various ways. The mudstone has developed a rough kind of cleavage which causes the beds to weather into flaggy masses, at a high angle to the bedding plane, while the rock exfoliates in flakes

FIG. 2.—Glaciated erratic (quartzite) from Cambrian till, north of Petersburg, S. Aus. ¾ natural size. *W. Howchin, photo.*

parallel to the cleavage. The lateral pressure has produced some interesting effects with respect to the included erratics. Those which possess unequal diameters have been caused to rotate in their beds until the longer axis of the stone has been brought into line with the planes of cleavage. This movement of the stone in its bed has produced a kind of laminar investment around the stone, imparting to the latter a skin of sericitic mica. Some of the stones show evidences of abrasion and carry pressure striae. This pressure striation can be easily distinguished from glacial striae. The former occurs as parallel lines, often raised, and covering most, if not all, the surface of the stone, and not unfrequently radial in direction; while the glacial striae are in the form of single

scratches, cross each other in various directions, and are cut into the stone to varying depths. Most of the elongated erratics are fractured transversely, with numerous gaping fissures which are sometimes filled with fibrous quartz (illustrated in Fig. 1). These fractures have probably resulted from strain acting along the planes of cleavage which has pulled the stone apart in successive planes.

It is a somewhat difficult task to restore, in imagination, the physiographical conditions that prevailed at the remote period

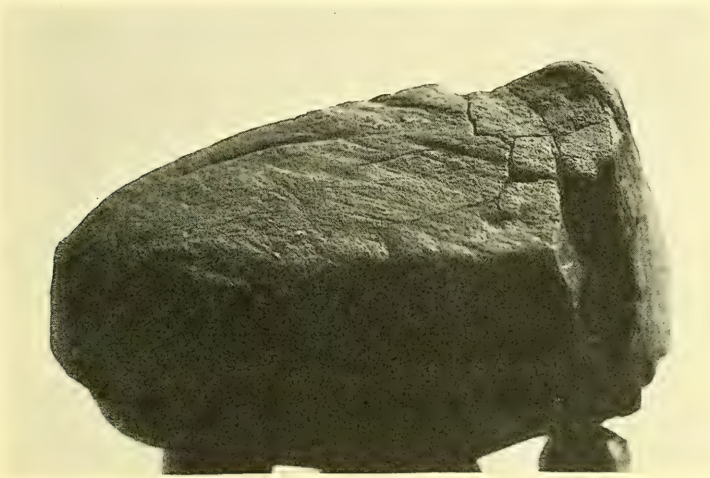

FIG. 3.—Glaciated erratic (quartzite) from Cambrian till, Umberatana, Flinders Range, S. Aus. $\frac{1}{2}$ natural size. *W. Howchin, photo.*

when this morainic material was laid down. From the nature of the evidence it is believed that the chief agent involved in laying down so vast a sheet of glacial débris was floating ice in an open and extensive sea. This sea was probably bounded on the south and west by moderate highlands, consisting of pre-Cambrian (Algonkian) quartzites, schists, limestones, and other sediments with exposed igneous batholiths and dikes of varied types. The pre-Cambrian complex had been subjected to great waste and was probably in the form of subdued relief at the time of the Cambrian glaciation. Remnants of this pre-Cambrian continent are

found in the geological axes of the Mount Lofty ranges, Yorke Peninsula, and Kangaroo Island; the crystalline ranges of Eyre Peninsula, the porphyrite outcrops of the Gawler ranges, and the igneous and metamorphic plateau of Western Australia.

In no instance has a glaciated floor been observed, the occurrence of which would suggest the probability of ice action above sea level. The absence of such an ice-marked floor, over the area in question, is not, however, to be wondered at when in no case have the glacial deposits been discovered in contact with a pre-Cambrian surface. The Cambrian till is found resting conformably on laminated quartzites in an orderly succession, and while the junction between the respective beds is always sharp and decided, it seems moderately certain that the glacial débris was laid down on a floor of contemporary marine deposits—in which case the agent of distribution must have been floating ice. This view is supported by the fact that the glacial material forms, practically, one continuous sheet, spread over an immense extent of country, and maintains a remarkable uniformity as to thickness, lithological characteristics, and types of erratics throughout its entire extent. At the same time it is very probable that the ice-field was at no great distance from this area of deposit. Two glaciated erratics, composed of a very characteristic graphic granite occurring in the pre-Cambrian series of Yorke Peninsula, were found by the writer in the till on the Petersburg ranges, their probable source being 150 miles to the southwest of where they were discovered. Among the erratics contained in the till, one of the most abundant is a porphyrite, which appears identical with the rock which comprises practically the whole of the Gawler ranges situated due west of the glacial deposit (I).

PERMO-CARBONIFEROUS GLACIATION

In its variety of features, wide distribution, and stratigraphical development, this must be regarded as by far the most important of the three periods of glaciation in Australasia. Glacial deposits of this age are represented in each of the Australian states, including Tasmania. In South Australia and Victoria the evidences are conclusive for the existence of land-ice during the Permo-

Carboniferous period, while in the case of the other states the morainic material is at places intermixed with sediments containing remains of marine organisms which suggests a distribution, in part, by means of floating ice.

SOUTH AUSTRALIA

The earliest recognition of ice-marks, on the Australian continent, was made by A. R. C. Selwyn in 1859, when engaged by the South Australian government to make a geological reconnaissance of the country. In his official report he said:

> At one point in the bed of the Inman I observed a smooth striated and grooved rock surface, presenting every indication of glacial action. The bank of the creek showed a section of clay and coarse gravel or drift, composed of fragments of all sizes, irregularly imbedded through the clay. The direction of the grooves and scratches is east and west in parallel lines, or nearly at right angles to the strike of the rocks; and though they follow the course of the stream, I do not think that they could have been produced by the action of the water, forcing pebbles and boulders detached from the drift, along the bed of the stream. This is the first and only instance of the kind I have met with in Australia, and it at once attracted my attention—strongly reminding me of the similar markings I had so frequently observed in the mountain valleys of North Wales.

Selwyn offers no suggestion as to the age of the glaciation.

Eighteen years later (1877) the late Professor Ralph Tate (IV), of the University of Adelaide, announced his discovery of a glaciated pavement at Hallett's Cove, situated on the coast, 15 miles south of Adelaide and 30 miles north of the glacial discovery made by Selwyn. The polished and striated surfaces are exposed at intervals, for about a mile on the top of the sea cliffs consisting of purple slates and quartzites of Cambrian age. Tate, in the first instance, considered the glaciation to be synchronous with the Pleistocene glaciation of the northern hemisphere; but this view, on further evidence, was shown to be incorrect.

The Hallett's Cove glaciated surfaces are of a *roche moutonnée* type, extending inland for a quarter of a mile, and are covered with glacial drift, which, again, is overlain by marine beds of Miocene age. The morainic material fills in an excavated valley in the Cambrian beds, forming the "Cove," and while giving a

thickness of 100 feet above sea level, passes under water to an unknown depth. The glacial deposits consist mainly of a bowlder clay carrying erratics of all sizes up to many tons in weight. Many of the included stones are powerfully glaciated.

It was subsequently found that Hallett's Cove glacial features represented only a small outlier of a glacial field of far greater extent. In 1897, Professor T. W. E. David and the writer visited the Inman Valley with a view to the rediscovery of Selwyn's "glaciated rock." Near the seventh milepost from Victor Harbor a very fine polished, grooved, and striated surface of hard quartzite was discovered partly bared in the banks of the Inman River. At the same time numerous large erratics, foreign to the locality, were seen either fixed in bowlder clay, or distributed along the hill sides adjacent to the river. The river bed was also, in places, thickly strewn with these erratics, some of immense size, washed out of the adjacent clay.

As the result of observations, spread over a number of years, it is possible to gather some general ideas of the magnitude of the ice-flood. A sheet of morainic material, accompanied in many places with transported stones of large size, covers most of the southern portions of South Australia, east of Spencer Gulf;[1] including the southern half of Yorke Peninsula, Kangaroo Island, and Cape Jervis Peninsula from the Willunga ranges on the north to the sea on the south and the Murray plains on the east, an area that may be roughly estimated as 100 miles by 130 miles. It is highly probable that these deposits formerly extended much farther north than their present occurrences, for outliers of the till are found in sheltered situations along the shores of Gulf St. Vincent and have been proved by borings to extend to a great depth below its waters. Important tectonic movements, in late Cainozoic times, brought these beds, in their northern extension, under conditions of rapid waste, which has probably led to the wiping out of the evidences of their occurrences in that direction.

In one respect the South Australian Permo-Carboniferous glaciation possesses a distinctive feature of great interest, inas-

[1] Eyre Peninsula, on the west side of Spencer Gulf, has not up to the present been examined for the discovery of glacial evidences.

much as the old glacial topography and surface features have been largely preserved, to the present day, throughout hundreds of square miles of country. This remarkable preservation of very ancient land forms has followed from a series of fortunate circumstances: first, because the original relief became protected by vast accumulations of transported material; and, second, because throughout most of the Cainozoic periods the glaciated area was below sea level and thereby became further protected by marine deposits. No important lateral movements occurred during the intervals to disturb the horizontality of the beds. An elevation took place in late Cainozoic times, with the result that the marine deposits have all but disappeared from exposed situations; and now, with the further erosion of the underlying morainic material, the old-world hills and valleys, that had been carved into outline by an ice-sheet in late Paleozoic times, are slowly being unburdened and once more make the surface features. The conditions that prevailed over this area during Mesozoic times are doubtful. No rocks of the latter age are known to exist in the southern portions of South Australia, but the preservation of the glacial beds, dating from pre-Mesozoic times, would seem to indicate that during those periods the beds must have been either at, or below, base level.

It is possible to gather a rough idea of the land features as they existed in southern Australia during this ice period. It is clear, both from the direction of the striae and the dispersal of the erratics, that the ice-sheet came from the south. At that time the main axis of elevation was to the south of the present continent, with upland valleys that opened out toward the north. Remnants of such uplands are preserved in the great granitic zone, the northern margin of which is seen in the prominent headlands and coasted islands. These southern highlands probably disappeared, in the main, when by a great *Senkungsfeld* along the southern limits of the continent, in early Cainozoic times, the land became submerged and admitted the sea over a wide belt of country. That this old watershed of the south had become greatly reduced—probably to an elevated plateau—at the period of glaciation, is suggested by the preponderating number of granitic rocks among the erratics.

Earth movements that have subsequently transpired have, in places, obscured the evidences of glaciation. A regional uplift, followed by extensive block faulting, occurred during the later Cainozoic times, when the Willunga and Mount Lofty ranges were elevated, and Gulf St. Vincent was developed by a series of trough faults. The effect of these movements has been to remove, through waste, the greater part of the morainic material from the elevated plateau, but at the same time the *Senkungsfeld* of Gulf St. Vincent has tended toward their preservation. A government bore put down, recently, at sea level, near Kingscote, Kangaroo Island, proved the glacial beds from the surface down to a depth of 1,094 feet, where they rest on Cambrian slates.

While it is clear that the ice, in some of its stages, was sufficiently thick to pursue a course quite independent of the local contours, the valleys have retained the greatest evidences of ice erosion. It is probable that the main glacier, within the area now under description, flowed down an upland valley that was in later times submerged through the land receiving a tilt to the south, and is represented by Gulf St. Vincent at the present time. The bore at Kingscote, just referred to, probably penetrated this main valley, choked with its morainic material.

The more interesting features of the glacial field are associated with what must be regarded as a glacier tributary to that which filled the depression of the Gulf. This tributary glacier occupied a wide valley, now drained by the Hindmarsh and Inman rivers and the Back Valley creek, together with their intermediate ridges, having an average width of 5 miles. The valley, at present, is truncated by the sea at its southern end, and follows a northwesterly course, up stream, passing over the present watershed of the Bald Hills and unites with the sea again at Normanville, on Gulf St. Vincent, having a land course of about 20 miles.

The great interest attaching to the valley of the Inman, is in the glacial topography which it exhibits in very remarkable features throughout. The deepest floor of the valley, so far as at present known, was proved by a bore in Back Creek valley which penetrated 964 feet before touching bed rock and was in glacial till, sandstones, and bowlders throughout. This depth, added to

the height of the morainic material within the valley, gives a thickness of not less than 1,500 to 1,600 feet for the deposit.

FIG. 4.—Polished, grooved, and striated pavement, 100 yards in length, covered by 9 feet of bowlder clay that contains erratics up to several feet in diameter. Exposed by a recent washout that cuts through the till down to the glaciated floor. The pavement is also seen in adjacent washouts proving the glaciated area to be over an acre in extent. Inman Valley, S. Aus. *W. Howchin, photo.*

The Inman Valley is bordered on either side by ranges of Cambrian and pre-Cambrian rocks, which form upland plateaus from 1,000 to 1,800 feet high. While glacial evidences are not absent

from these highlands, the most striking features are developed within the valley proper. The spurs of the ranges are rounded, truncated, and shouldered in a very characteristic manner. The prominent points of the piedmonts, as well as the inliers of hard rock showing above the glacial deposits of the valley, are strongly glaciated, exhibiting *roche moutonnée* outlines on a large scale, and in many places showing polished and deeply scored surfaces (see Fig. 4). The crag and tail outline is always present in these

FIG. 5.—Permo-Carboniferous *roche moutonnées*, of quartzite (partly quarried) at the entrance to the Inman Valley. The intermediate country, of scrub land, consists of glacial deposits, and, in the distance, is seen the gigantic *roche moutonnée* of Crozier's Hill. *W. Howchin, photo.*

rounded hummocks. The *Stossseite* maintains a gradual slope while the *Leeseite* is abrupt and broken, as when "plucked" by ice movements. The southern entrance to the valley is marked by two striking *roches moutonnées* surrounded by glacial till with granite bowlders, partly exposed, up to 9 feet in diameter (see Fig. 5). Crozier's Hill, 520 feet high, situated near the middle of the valley, is another striking example of the same kind. Strangways Hill, a prominent spur, nearly 900 feet high, on the northern side of the valley, was in the direct path of the glacier, but failed to divert its flow, as evidenced by powerfully glaciated pavements

on both sides of the hill, the striae in each case showing that the ice took a direct course over the ridge (see Fig. 6). The Bald Hills, which form the present water-parting between the two seas, were also overflowed by the ice-sheet. The summit and western side supply abundant evidences of this in ice-polished surfaces, glacial till, and large erratics.

Fig. 6.—Very strongly glaciated Permo-Carboniferous pavement of siliceous quartzite, 9 feet by 3 feet, on the southern slope of Strangway's Hill, Inman Valley. The striated floor, which is of unknown extent, is covered with bowlder clay, and the photographed portion was freshly uncovered by the writer. *W. Howchin, photo.*

The morainic material originally filled up all the inequalities of surface, reaching up to the level of the plateau country, some 1,500 feet above present sea level. This, with the 1,094 feet in the Kingscote bore near sea level, gives a total thickness for the glacial deposits of about 2,500 feet. If the trough-fault of Gulf St. Vincent extends to Kingscote, it is possible that these figures are too high, being exaggerated by such faulting.

The glacial deposits vary from a stiff blue clay to sandstones. The clay is often gritty and carries pockets of sand and stones, with isolated larger stones up to 20 feet in diameter. Many of the included erratics are strongly glaciated (see Fig. 7). The sandstones are of very unequal hardness, varying from a loose friable stone to a highly indurated or siliceous rock, and are often pebbly.

FIG. 7.—Glaciated erratic of quartzite, taken from Permo-Carboniferous bowlder clay, in washout at Poole's Flat, near Normanville, S. Aus. ½ natural size. *W. Howchin, photo.*

The planes of deposition are distorted in places and the microscopic structure of the stone gives striking contrasts. In the same section, highly rounded quartz grains are mixed with angular and splintery quartz, and in some cases the stone is entirely composed of the latter. The ground mass consists of exceedingly minute fragments of comminuted quartz known as "rock-flour." The sandstones are quarried in places for road metal and building stones. The sandstones are mostly characteristic of the upper members of the series and the bowlder clays of the lower. In the extensive dis-

tricts of Mount Compass and the River Finniss the bowlder clays form broad valley flats, which, from their retention of water, give rise to numerous swamps.

The geological age of the South Australian beds is largely a matter of inference. They rest on a Cambrian or pre-Cambrian floor, and are overlain in places by marine deposits of Lower Tertiary age, the latter resting on the eroded surfaces of the tillite. In lithological characteristics the South Australian deposits show a close resemblance to the Victorian glacial beds, the age of which can be demonstrated. This, together with the impossibility of finding any other glacial horizon in Australasia with which the beds in South Australia can be synchronized, forms the basis on which the deductions as to age have been made (IV–XII).

VICTORIA

The first observations of glacial evidences in Victoria were made by Mr. (Sir) Richard Daintree, a member of the Geological Survey, who in 1866 reported the occurrence of glacially striated pebbles in the valley of the Lerderberg River, near Bacchus Marsh. Little notice was taken of this discovery till 1890, when Mr. E. J. Dunn, now director of the Victorian Geological Survey, read a paper on the subject before the Australian Association for the Advancement of Science (XIII). Two years later the same author published a more particularized account of similar glacial beds occurring in Wild Duck Creek, in the Heathcote district (XIV). The Victorian Permo-Carboniferous beds have been further described by Messrs. Officer and Balfour (XV), Messrs. Sweet and Brittlebank (XVI), and others.

The localities where the glacial beds are developed are both numerous and widely distributed, but in no one case cover a very large area. They occur on both sides of the Dividing Range, in basins and protected situations, as fragments of what once must have been a widely extended sheet of drift. The chief localities on the north side of the Dividing Range are in the districts of Springhurst and Beechworth, near the northeast borders of Victoria; the neighborhood of Greta, where a number of isolated

outcrops occur; Wild Duck Creek and neighborhood, near Heathcote; and still farther to the west, at Bendigo and the Loddon Valley, where the glacial beds outcrop in the creeks and are also met with in sinking on the deep leads, underlying basalt. On the south side of the divide the principal localities are grouped near Bacchus Marsh, adjoining the Adelaide and Melbourne Railway, with excellent sections in the valleys of the Lerderberg River, Myrniong Creek, and the Korkuperrimal Creek.

The glacial beds rest unconformably on Ordovician and Silurian rocks, which, in both the Heathcote and Bacchus March districts, exhibit polished and striated pavements. The beds of the Wild Duck Creek section are 400 feet in thickness and can be traced for more than 15 miles in length. The till carries numerous erratics, some of which are estimated to weigh 20 to 30 tons.

In 1896 Professor T. W. E. David published a comprehensive description of the Bacchus Marsh area, accompanied by detailed sections (XVIII). The glacial beds are characterized by hard and soft mudstones, conglomerates, and sandstones, having a prevailing dip ranging from 15° to 60°, and an estimated thickness of 2,000 feet. The mudstones or bowlder beds have the appearance of a typical tillite, and in their softer portions might have been mistaken for a Pleistocene glacial till. These mudstones make up the greater part of the section and are interstratified with thinnish sandstones. The thickest till bed in the series, according to David, measures 193 feet. The included erratics are very plentiful, exhibit a great variety of lithological types, and, in many instances, are irregularly worn, smoothed, soled, and striated (XVIII, p. 297).

The Bacchus Marsh section passes up into variable sandstones carrying, in places, patches of conglomerate. These sandstones are of considerable interest as they contain plant remains which determine the age of the beds. Among these are three species of *Gangamopteris*, and at a somewhat higher horizon, *Zeugophyllites*, *Schizoneura*, and others. These remains, taken in conjunction with their occurrences in other parts of Australia, determine the beds to be of Permo-Carboniferous age.

The evidence that the glaciation of Victoria in Permo-Carboniferous times was effected above sea level and by land-ice

seems conclusive. There is an entire absence of marine deposits throughout the sections, while the existence of polished pavements in suitable situations beneath the bowlder clay cannot well be explained by any other hypothesis.[1] In this particular the Victorian glaciation agrees with the South Australian of the same age, but there has occurred in the sequel a greater tectonic activity in Victoria than in South Australia, which has disturbed the surface contours and wiped out most of the contemporaneous glacial topography that is so striking a feature in South Australia.

TASMANIA

Rocks of Permo-Carboniferous age are very generally distributed throughout Tasmania. They give evidence of alternations of dry land with fresh water and shallow marine conditions. In places they contain productive coal measures. During the early stages of this geological period the present island of Tasmania formed part of the continental mass, and came under the glacial conditions which laid such a heavy hand on Australia at that time.

The locality most favorable for the study of the glacial beds of Tasmania is on the north coast, in the neighborhood of Wynyard, where for a distance of five miles the bowlder beds are exposed along the beach. The beds dip at rather a low angle (5°–10°), have a thickness of over 1,200 feet, and are overlain by fossiliferous beds of Eocene age. The beds, which have been worked out in great detail by Professor T. W. E. David (XXIII), consist, lithologically, of characteristic tillites and conglomerates, all of which carry glaciated stones in greater or less numbers; and these are interbedded by thinner members consisting of sandstones and laminated shales. No glaciated floor has been discovered either here or elsewhere in Tasmania. The rotten Ordovician slates, on which the beds rest at Wynyard, are unsuited for the preservation of such a smoothed pavement, but the entire absence of marine remains throughout the very thick glacial series suggests the terrestrial origin of the deposits.

[1] A polished surface beneath the bowlder clay in the Bacchus Marsh district is figured by Gregory, in his *Australasia*, p. 416 (Stanford's "Compendiums of Geography," New Issue, 1807).

Among the included erratics are angular masses of slate carrying Silurian fossils. The nearest source for such erratics, according to Mr. W. H. Twelvetrees, is upward of 30 miles to the southwest of Wynyard; while examples of a pink granite, which also occurs as bowlders in the till, is not found nearer than the ranges, also to the southwest, and about the same distance away. The most angular blocks contained in the till consist of graptolitic slates, resembling the rocks of the immediate neighborhood, a strong argument in favor of the agency of land ice. The erratics are mostly of moderate size but are found up to 5 feet in diameter, and, on the statement of Professor David, a large proportion is intensely glaciated.

An interesting feature in the Wynyard beds, discovered by Professor David, was the existence of striated pavements in the body of the till, at three distinct horizons. Concerning these he says,

> As a rule striated pavements were not observed in the bowlder clay where it was of considerable thickness, such striated pavements as were noticed appeared to be restricted to thin patches of bowlder clay interbedded with conglomerate. . . . . In most cases the grooving and striation is about N. 30° E., that direction being the lee side so that the ice in this locality evidently moved from about S. 30° W. toward N. 30° E. (XXIII, p. 277).

In the southern portions of Tasmania the Permo-Carboniferous glacial beds crop out at about sea level, along the intricate coastline and islands of the southeast. Good sections are seen on Bruni Island (One Tree Point), where, Mr. R. M. Johnstone says, "waterworn and angular fragments of granite, altered slates, porphyries, quartzites, and greenstones (rocks unknown in the vicinity) are most abundant. Some of the blocks are huge" (XIX, p. 121). Similar exposures are found in Maria Island (Darlington), where the glacial beds are overlain by a rich marine fauna, especially characterized by *Eurydesma cordata* and *Pachydomus*, typical *Permo-Carboniferous* forms of the mainland. Other localities are at the mouth of the Huon River, opposite Port Cygnet; and on the northwest coast, in the neighborhood of Strahan and northward, where the glacial outcrops have been noted by Dunn, Kitson, Officer, and Gregory.

In the majority of cases the glacial deposits of Tasmania (of this age) appear to have been laid down under the agency of land-ice, but in a few localities, as in the fossiliferous mudstones of the Derwent, near Hobart, sporadic bowlders occur mixed with a marine fauna in a way that is suggestive of floating ice.

NEW SOUTH WALES

The Permo-Carboniferous rocks of New South Wales occupy an area of about 26,000 square miles and are by far the most important development of rocks of this age in Australasia. They owe their existence to a great monoclinal fold which, on the western side, formed the Blue Mountains; and on the eastern, the great geosyncline that supplied the conditions for the building up of a vast coal field. This basin, including the Triassic beds which constitute the upper portion of the basin, is about 17,000 feet in thickness.

The Permo-Carboniferous series consist of the following main divisions:

1. Upper, or Newcastle Coal Measures (fresh-water beds with productive coal), about	1,500	feet thick
2. Dempsey Series (fresh-water without productive coal), about	2,000	" "
3. Middle or Tomago Coal Measures (productive), about	1,000	" "
4. Upper Marine Series (*includes the Branxton glacial beds*), about	6,400	" "
5. Lower, or Greta Coal Measure, about	200	" "
6. Lower Marine Series (*including several horizons of glacial beds*), about	4,800	" "

The flora of the fresh-water beds is especially characterized by *Glossopteris*, *Noeggerathiopsis*, *Gangamopteris*, *Sphenopteris*, etc., while the marine beds yield an abundant fauna of a distinctly Carboniferous facies, with such genera as *Lithostrotion*, *Cyathophyllum*, *Zaphrentis*, *Favosites*, *Productus*, *Chonetes*, *Orthis*, *Spirifer*, etc.

Glacial erratics are met with at various horizons both in the Lower Marine series and the Upper Marine series, and have been found in many localities. The two main horizons for glacial

evidences are the Branxton[1] beds, in the Upper Marine, and the Lochinvar beds, which form the base of the Permo-Carboniferous rocks.

The first definite discovery of glaciated stones, in New South Wales, was made by Mr. R. D. Oldham, the superintendent of the Geological Survey of India, who when visiting Branxton, in 1885, was much struck with the resemblance which the beds in this locality bore to the Talchir glacial beds of India, belonging to a similar geological age, and was confirmed in this opinion by the discovery of a distinctly glaciated erratic which he subsequently described.[2] The Branxton beds are chiefly sandstones, very rich in *Fenestellidae*. Erratics occur in these beds up to 4 feet and 5 feet in length, and frequently indent the floor on which they were dropped (XXVI, p. 198, pl. XXIV).

The important exposure of glacial beds, near the township of Lochinvar (on the railway 102 miles north of Sydney), was discovered by Professor David and others while carrying out geological survey work in 1899. These beds are about 300 feet in thickness, and rest unconformably on rocks of Carboniferous age. They have a very close resemblance to the Bacchus Marsh till beds and contain numerous glaciated stones. David says,

> The included bowlders in the glacial beds vary in size from a few inches up to about two feet. The bowlders consist of quartzite, sandstone, argillite, granite, diorite, greenish felsitic (?) rocks, serpentine, etc. Perhaps from five to ten per cent, more or less, were originally glaciated, but owing to redistribution and attrition in probably shallow sea water it is exceptional to find bowlders which have retained well-defined grooves or striae. The bowlders vary from angular to rounded, and, unlike those at Branxton and Grasstree, these exhibit distinct grooves as well as striae, in this respect resembling those of Bacchus Marsh.

Two glaciated stones are figured by David, the one from Branxton and the other from Lochinvar (XXV, p. 154, pl. IV). The section (300 feet) is entirely devoid of fossil remains, but at the extreme top of the beds, *Spirifer* and *Eurydesma* make their appearance. David estimates the horizon of the Lochinvar beds

[1] Branxton is on the main north line from Sydney, in the Maitland district, and Lochinvar is situated on the railway, about 8 miles nearer Sydney.

[2] *Rec. Geol. Survey of India*, XIX, p. 44.

to be, approximately, between 5,000 and 6,000 feet below that of the Branxton erratic horizon. There are, however, several other horizons, intermediate to those mentioned, in which glaciated stones occur.

QUEENSLAND

The equivalents of the New South Wales Permo-Carboniferous Coal Measures occur in Queensland as the Middle and Upper Bowen River series, extending from $20\frac{1}{2}°$ S. to 26° S. (The Lower Bowen beds consist mainly of igneous rocks and are referred to the Carboniferous.) The beds are characterized by marine sandstones and shales, interbedded with fresh-water deposits and a few seams of rather poor coal, believed to be representative of the Greta Coal Measures horizon of New South Wales. Near the base of the series there are conglomerates, isolated pockets of stones, and according to Jack and Etheridge (XXVII, p. 151), "large isolated bowlders of granite, etc., which could hardly have been brought to their present positions except by glacial action, as they occur here and there in the midst of strata of fine sandy or muddy material."

These Queensland occurrences have not been very extensively examined, and the glacial evidence is not very definite, but the presence of stones, sporadically present in fine sediments, on the same horizon in which clear evidence of glacial action is present in other parts of Australia, offer strong presumptive evidence of a similar origin in the case of the Queensland beds.

WESTERN AUSTRALIA

The main development of Permo-Carboniferous rocks in Western Australia occurs to the north of Perth, in an area of variable width running parallel with the coast for about 450 miles. The more interesting localities are found on the Irwin River, Gascoyne River, and the Minilya River. The beds carry a marine fauna that is distinctly Carboniferous in type.

In the year 1900, Mr. A. G. Maitland, government geologist, reported the "discovery, associated with the Carboniferous rocks of the Wooramel and the Minilya rivers, of an extensive deposit

of glacial origin" (XXVIII, p. 28), and figured four glaciated bowlders (plate IV) from these localities. The deposit was proved to exist for a distance "considerably over sixty miles."

In *Bulletin No. 10*, Geological Survey of Western Australia, plate VI, Mr. Maitland maps the approximate line of outcrop of the "glacial conglomerate" between the Wooramel and Minilya rivers.

Mr. Maitland, in a presidential address (XXIX, p. 146), gave further particulars and says,

> At the most southerly locality at which the bowlder bed has been detected in Wooramel Valley, the bowlders are of very large size, and are composed of rocks identical in character with those forming the older underlying rocks to the east, e.g., granite and other crystalline and metamorphic rocks. Some distance northward, on the Wyndham River, is a bowlder bed in the limestone series. The bed, which at this spot attains no greater thickness than 3 ft., is crowded with bowlders and pebbles of granite and crystalline rocks embedded in a calcareous fossiliferous matrix . . . . the pebbles and bowlders have a large proportion of smooth and polished faces.

The same beds are further described by Maitland in their northern extension to the Minilya River.

Assistant Government Geologist, W. D. Campbell, in a detailed examination of the Irwin River Coalfield (situated 300 miles to the south of the Gascoyne, where Maitland's observations were made), paid special attention to the glacial beds of the section and has supplied interesting photographs of the features (XXX). He refers the glacial beds to the middle of the Permo-Carboniferous series, or about the horizon of the Greta Coal Measures of New South Wales. The erratics comprise granite, gneiss, amygdaloids, quartzites, sandstones, chalcedonized sandstones, and limestones, mostly rounded and many with smoothed surfaces and some with well-defined grooves and cross-scratchings, such as only glacial action can produce. These form in places extensive bowlder beds or outcrops which occur at distances of from 5 to 10 miles from the main granite margin. These erratic blocks are mostly identifiable with rocks forming the tableland eastward of the main granite range. The largest outcrop of the bowlder beds is on the west side of the Irwin River, at Nangatty, and is about 4 miles long and 2 miles wide (XXX, p. 39, pls. XIV–XVIII).

GENERAL REMARKS ON THE PERMO-CARBONIFEROUS GLACIATION

It is quite clear that the glaciation within the geographical limits of the present continental mass during Permo-Carboniferous times was both terrestrial and marine, probably more of the former than the latter, but it is not always possible to say to which of these conditions the effects have to be referred.

Wherever striated pavements occur, the direction of the ice movement is seen to have been from south to north. The striated pavements in the till, at Wynyard, Tasmania, described by Professor David (XXIII, p. 277), shows the direction of flow as N. 30° to 35° E. In the Bacchus Marsh district, Victoria (at Coimadai), described by Officer, Balfour, and Hogg (XVII, p. 326), the direction of the striae is from southwest to northeast; and in the same district, more to the south and west, Sweet and Brittlebank supply similar readings (XVI, p. 378). In the bed of the Inman, South Australia, David and Howchin found the glacial striae to vary from W. 9½° N. to W. 12° N. (VI, p. 117). On a pavement 100 yards in length, on higher ground to the east of the last named, the present writer found the striations to read W. 10° N.; and on another polished floor in the neighborhood, at the base of Strangways Hill, the same reading was obtained. On the other side (north) of Strangways Hill, at the head of the Duck's Nest Creek, the direction was found to be northwest. At Hallett's Cove, in Gulf St. Vincent, 40 miles north of the Inman Valley, Tate, Howchin, and David found the general trend of the grooves to be nearly north and south (V, p. 316).

This remarkable agreement in the direction of the striae over so great an extent of country is suggestive of the magnitude of the ice movements, and also that the center of distribution must have been to the south of the present limits of the continent. The northwesterly trend of the ice in the Inman Valley district can be explained, inasmuch as this sheet was a tributary to the main glacier which flowed up what, at present, forms the drowned valley of Gulf St. Vincent.

To the action of land ice may be confidently referred the morainic deposits of Wynyard, in northern Tasmania; the deposits and glaciated surfaces on either side of the Dividing Range, in

Victoria; the ground moraines and extensive *roche moutonnée* features of Cape Jervis peninsula and at Hallett's Cove, in South Australia; the Lochinvar bowlder beds, at the base of the Permo-Carboniferous series, in New South Wales; and probably, the tillites of the Irwin River district, in Western Australia. The last two localities are, respectively, in about $32\frac{1}{2}^{\circ}$ and 29° south latitude. In the more northerly localities, as Minilya, in Western Australia, situated on the Tropic of Capricorn, and the Bowen River beds, of Queensland, which are situated a few degrees within the tropics, the evidence is uncertain, and the deposits may have been laid down by floating ice. The same thing is also likely to have occurred on the south coast of Tasmania, and in some localities of New South Wales. Such marine glacial deposits may have been synchronous with a partial submergence of the continent, following the maximum glaciation, as was the case in the Pleistocene glaciation of the Northern Hemisphere.[1]

PLEISTOCENE GLACIATION

The glaciation that occurred in Australia during Pleistocene times was limited to the southeast highlands of the present continent and the greatest altitudes in Tasmania.

NEW SOUTH WALES

Mount Kosciusko (7,328 feet), on the borders of New South Wales and Victoria, is the culminating point of an extensive upland plateau, forming the angle or knot, where the meridional mountains of the eastern coast unite with the occidental mountains of the southern coast. At the present time there is no permanent snow field in either Australia or Tasmania, although in sheltered

[1] Dr. O. Feistmantel, in discussing the question of the correlation of the Permo-Carboniferous flora and glaciation as respectively developed in Australia, India, and South Africa, says: "But I do not think it was contemporaneous over that whole region, and it appears to me that it (the glaciation) set in first in Eastern Australia, (New South Wales,) destroying the Carboniferous flora at an early date, while in southern Africa we find still a Carboniferous or Coal measure flora of a higher stage, and only thereafter the change of climate appears to have taken place there."—"Geological and Paleontological Relations of the Coal and Plant-Bearing Beds of Paleozoic and Mesozoic Age in Eastern Australia and Tasmania," *Mem. Geol. Survey of N.S.W. Pal. No. 3*, 1890, p. 181.

nooks snow lies on these uplands most of the year, and snow storms may occur in the height of summer. At sea level, in the same latitude as Kosciusko, the mean annual temperature is about 59° F., while the present mean temperature of the summit of Kosciusko is about 35° F.

The first definite and unquestionable determination of glacial features on Kosciusko was made by Dr. R. von Lendenfeld, in 1884 (XXXI). Lendenfeld's observations were limited to the occurrences of *roches moutonnées* and glacier-polished rocks, which he found in the Wilkinson Valley, situated between Mount Kosciusko and Mount Townsend, at the sources of the River Murray, in the upper valley of the Snowy River, and also in that of the Crackenback River. The polished faces were found on prominent surfaces (one of them was 3 acres in extent), and was estimated to extend, in all, over 100 square miles of country. Lendenfeld believed that the lowest altitude of glaciation was 5,800 feet above sea level. On account of Lendenfeld's observations not being supported with collateral evidences, some skepticism was expressed as to the existence of true glacial features in the area described by him.[1]

Mr. R. Helms, in a visit to Kosciusko in 1893, supplemented Lendenfeld's observations in several important particulars. He noted the glacial topography of the country, with respect to the occurrences of flat bottom valleys; glacial moraines, (one of which was over a square mile in extent); glacially excavated lakes, as in the case of Lake Merewether (or Blue Lake); and transverse moraines, causing moraine lakes. He placed the lower limits of glacial action at about 5,200 feet above sea level (XXXIII).

More detailed work on the field was done by Professor David, (in conjunction with other scientific experts), who visited Mount Kosciusko on four separate occasions (1901–8), with the result that the question of glaciation of the Australian Alps, within comparatively recent times, has been placed beyond dispute (XXXIV–XXXV).

One important point which these later observers claim to have established is that there have been two periods of glaciation on

[1] See a discussion on the subject in Geological Society of London, *Quar. Jour. Geol. Soc.*, XLI (1885), Proc. p. 103.

the Kosciusko highlands. The earlier one was the more extensive and produced "U-shaped valleys, hanging valleys, filled-up lake basins, and smoothed rock surfaces"; while the later period has left its evidences in "*roches . . . . moutonnées* and grooved and striated rock surfaces, erratics and perched blocks, terminal and lateral moraines."

The ice-fields were much more extensive on the eastern side of the main divide than on the western.

> During the maximum glaciation the ice-sheet extended to at least 12 miles N.E. from Mount Kosciusko, and moved in a general S.E. to E.S.E. direction from the main dividing range between the Snowy and Murray rivers, toward the valley of the Thredbo. By far the greater portion of the ice-sheet, or calotte, lay to the S.E. of the main divide, and spread to a distance of probably at least, 7 miles at right angles to the former (XXXV, p. 665).

The longest glacier occupied the Snowy River Valley and came down to 4,500 feet above the present sea level, while "the total area covered by the ice-calotte of Kosciusko during the maximum glaciation was probably about from 80 to 100 square miles" (XXXV, p. 665). During this period the ice-sheet, in places, had a thickness of not less than 1,000 feet, "as it was able to cross the Snowy Valley and override Charlotte Pass Valley, the whole of Spencer's Creek Valley, and plunged over the southeastern edge of the plateau into the Thredbo Valley."

Smaller glaciers occupied the western side of the divide, especially in the Wilkinson Valley, where terminal moraines gave rise to Lake Albina; other moraines, more to the southwest, led to the formation of Lake May (L. Cootapatamba) and others. The glaciers on this side came down about 1,000 feet from the summit, or about 6,300 feet above sea level. The reason for this difference in the respective sizes of the ice-fields on either side of the divide is explained by Professor David on the ground that the strong anti-trades (W.N.W.) carried much snow over the crest on to the lee side, where the slope of the ground was more gradual than on the western, and thereby permitted thicker accumulation of névé.

Some of the more interesting features of the newer glaciation are to be found in connection with the Blue Lake (Lake Mere-

wether), the largest of the numerous glacially formed sheets of water which occur within the limits of the old ice-field. The Blue Lake, in the first instance, was formed as a rock basin during the earlier glaciation, but took its present form in the later stages. Its waters are dammed back on the outlet side by a huge transverse moraine, which is about 20 chains wide and rises to a height of 160 feet above the level of the lake. To test the depth of the lake, Professor David, in January, 1906, constructed a coracle on the spot, built of gum sticks, American cloth, and wire netting, and with this extemporized boat took soundings, which proved the lake to be 75 feet in greatest depth. In the following month, Professor David returned, accompanied by Mr. Chas. Hedley, of the Australian Museum, Sydney, and by means of the same frail coracle, obtained dredgings from the bottom, that yielded three species of fresh-water annelids.

The skepticism as to the glacial origin of the smoothed surfaces on Kosciusko, which arose in the minds of some of the earlier observers, was based on the fact that much of the local rock surface gave no evidences of denudation, except what was capable of explanation by reference to ordinary subaerial agents. It is suggested by Professor David, as an explanation of this anomaly, that the present *roches moutonnées* have been protected through most of the year and for long ages by coverings of snow; while the exposed portions have been weathered into granite peaks and tors. The illustrations which accompany David, Helms, and Pittman's papers (XXXIV) place the question of a Pleistocene glaciation on the highest points of the Australian continent beyond all doubt.

In the determination of the approximate age of the glaciation, Professor David and others have fallen back on the data afforded by stream erosion since the retreat of the ice. At one place, in the Snowy River Valley, there is an old filled-up glacial lake (L. Andrews) with a rocky bar on its outlet side. In the U-shaped Snowy River Valley, the stream, since the disappearance of the glacier, has cut down a V-shaped gorge through a bar of hard granite to a depth of 60 feet. David thinks that this work of erosion stands for an equivalent of from 50,000 years to 100,000

years (XXXV, pp. 663–64), and that the period of maximum glaciation might be roughly estimated as occurring from 100,000 years to 200,000 years ago; but that the newer glaciation is separated from the present day by only some 10,000 years or 20,000 years.

TASMANIA

Physiographically Tasmania belongs to the eastern highlands of the Australian continent, from which it became separated by the *Senkungsfeld* of Bass Strait. The island consists of a great central plateau having an elevation of from 2,000 feet to 5,000 feet above sea level. Surrounding this central plateau is a still more extensive tableland, with an elevation from 1,200 feet to 2,000 feet, from which rise important mountain ranges and isolated peaks that reach elevations up to nearly 5,000 feet. As, within comparatively recent times, the Australian Alps of the mainland carried permanent ice-fields at levels below those of the higher mountains of Tasmania, it was reasonable to expect that the latter, situated some 5° or 6° farther south, would at the same period be ice-clad.

The testimony of early observers with respect to a Pleistocene glaciation in Tasmania was somewhat conflicting, and some confusion arose from the presence of an older glaciation, of Permo-Carboniferous age, occurring in close proximity to the newer glaciation.

The first definite evidences of a comparatively recent glaciation of Tasmania were obtained by E. J. Dunn and T. B. Moore who visited the West Coast Range, in company, in 1892, and published separate accounts of their observations in 1894 (XXXVII and XXXVIII). The West Coast Range runs north from the inlet of Macquarie Harbor, parallel with the coast, from which it is distant about 15 miles. The range is drained by the King River on its eastern flanks, and by the Queen River on its western. These mountains are capped, for the most part, with a very siliceous conglomerate of supposed Devonian age, which, from the nature of the rock, has preserved to the fullest extent such evidences of glaciation as occur in the polishing, grooving, and striation of rock surfaces. The valleys and lower slopes of the range

composed of schists—in which many rock basins have been excavated varying in size from small tarns up to lakes several miles in extent.

Dunn and Moore found *roches moutonnées* and striated surfaces on the flanks and almost to the very summits of Mounts Tyndall (3,875 feet), Sedgwick (4,000 feet), Geikie (3,950 feet), and others. Lakes Dora, Margaret, Ruby, and Rolleston lie in the valleys surrounding these heights, in the line of the extinct glaciers, and owe their existence either to excavated rock basins, or to banks of moraine. Lake Rolleston is impounded by a terminal moraine which crosses the valley in a high bank, 150 feet above the present valley on its eastern end, and 250 feet at its western. Scattered, perched, and lineal erratics occupy positions on the hillsides up to 300 feet above the level of the valley. The moraines are loosely and irregularly piled up, carrying stones of all sizes up to 100 tons in weight, many of which have been found glaciated and striated. The direction of the striae on rock faces vary at different points. A main glacier was fed from the north and northwest of Lake Rolleston, and the ice found its way down the principal outlet by the King River Valley. Another line of ice-flow, mentioned by Moore, was down the eastern slopes of Mount Owen, by the Linda Valley, and these joined on the main glacier of the King Valley. The moraines and other indications of ice movements were traced down to levels only 400 feet above sea level. Moore estimates that the ice had a thickness up to at least 1,000 feet.

The accuracy of Dunn's and Moore's observations in this field were fully confirmed by Professor J. W. Gregory, who, in the year 1900, went over the ground and still further increased our knowledge of the subject by valuable and independent observations. Gregory's original observations were mainly confined to the district around Mount Owen (3,800 feet) and Mount Lyell (2,744 feet). This observer says that Mount Owen, on its northern face, is "strikingly glaciated," and describes extensive moraines in the valley of the Linda as well as that of the King. The Gormaston moraine, on the eastern side of Mount Lyell Mine (in the upper Linda), takes its name from the township which it carried on its surface. It is a mile long by half a mile wide, and attains

a height above the Linda Creek of 320 feet. It is a typical glacial till. The included bowlders consist mainly of quartzites derived from the conglomerates that form the summits of Mount Owen and Mount Lyell. Some of the erratics in the till have come from a greater distance, as, for example, diabases, which belong to the mountain ranges and central plateau farther to the east.

The West Coast Railway passes through much of the glacial country, in its lower altitudes, and has numerous cuttings intersecting moraines. This is especially seen in that part of the line situated between Farrell and Zeehan. Some of the erratics at Farrel are of great size. One of Devonian Conglomerate, brought down by the ice from near the crest of the Ranges, measures 25 feet in greatest diameter. Gregory obtained from the till several distinctly glaciated bowlders.

As in the case of the Kosciusko glaciation of the mainland, the age of this recent glaciation of Tasmania is largely a matter of inference based on the physiographical changes that have transpired in the interval. In its main outlines Tasmania was, at that period, very much the same as it is today. From the direction of ice-flow, as well as the nature of the transported material, it is certain that the principal gathering fields were on the Central Plateau, the Eldon Range, and other heights to the east of the country examined and described. The freshness of the glaciated surfaces and the position, as well as the condition, of the valley moraines all point to a relatively recent glaciation, certainly not older than the Pleistocene.

Tasmania, in common with most of Southern Australia, has undergone considerable oscillations of level within recent periods. The drowned valleys of the Tamar, the Derwent, and Macquarie Harbor, as well as Bass Strait, are proofs of subsidence. On the other hand there are evidences of recent uplift. Moore's estimate that the ice in the King River Valley came down to within about 400 feet of sea level agrees with that of Gregory's in relation to the Pieman Valley. Gregory says:

> The bowlder clays of the Pieman Valley give the lowest level (400 feet above the sea) yet proved for the Tasmanian Pleistocene glaciers. It must be remembered, however, that there is certain evidence of a recent uplift of

this part of Tasmania to the height of several hundred feet, so that some of the glaciers may have actually reached sea level (XXXIX, p. 52).

More extended observations will probably show that in both Australia and Tasmania this latest of Australian glaciations was much more extensive than at present known.

In considering the climatic and physiographical conditions of Australasia in the Pleistocene period, it is important to take into account the greater development of glaciers in New Zealand at about that time (XL, XLI).

BIBLIOGRAPHICAL REFERENCES (SELECTED)

Cambrian Glaciation

SOUTH AUSTRALIA

(I) 1901. Howchin, W. "Preliminary Note on the Existence of Glacial Beds of Cambrian Age in South Australia." *Trans. and Proc. Roy. Soc. S. Aus.*, XXV, 10–13.

(II) 1906. ———. "The Geology of the Mount Lofty Ranges," Part, *Trans. and Proc. Roy. Soc. S. Aus.*, XXX, 228–34, pl. XII.

(III) 1908. ———. "Glacial Beds of Cambrian Age in South Australia," *Quar. Jour. Geol. Soc.*, LXIV, 234–59, figs. 1–12, pls. XIX–XXVI.

Permo-Carboniferous Glaciation

SOUTH AUSTRALIA

(IV) 1887. Tate, R. "Glacial Phenomena in South Australia (Hallett's Cove)," *Rep. Aus. Assoc. Adv. Science*, I, 231–32, Sydney.

(V) 1895. Tate, Howchin, and David. "Evidences of Glaciation at Hallett's Cove," *Rep. Aus. Assoc. Adv. Science* (Report of Glacial Research Committee), VI, 315–20, pls. XLIX, L.

(VI) 1898. "Report of Glacial Research Committee, South Aus. Evidences of Glaciation in the Inman Valley, Yankalilla, and Cape Jervis Districts," *Rep. Aus. Assoc. Adv. Science*, VII, 114–27, pls. II, III, and fig. in text (photographs of striated pavement and large erratic).

(VII) 1898. Howchin, W. "Further Discoveries of Glacial Remains in South Australia (Hindmarsh Valley)," *Trans. and Proc. Roy. Soc. S. Aus.*, XXII, 12–17.

(VIII) 1899. Howchin, W. "Notes on the Geology of Kangaroo Island, with Special References to Evidences of Extinct Glacial Action," *Trans. and Proc. Roy. Soc. S. Aus.*, XXIII, 1899, 198–207, pls. IV, V.

(IX) 1900. ———. "Evidences of Extinct Glacial Action in Southern Yorke Peninsula," *Trans. and Proc. Roy. Soc. S. Aus.*, XXIV, 1900, 71–80.

(X) 1908. ———. "Cambrian and Permo-Carboniferous Glaciation in South Australia," *Rep. Aus. Assoc. Adv. Science* (Glacial Research Committee), XI, 1907, 264–72.

(XI) 1910. ———. "The Glacial (Permo-Carboniferous) Moraines of Rosetta Head and King's Point, South Australia," *Trans. and Proc. Roy. Soc. S. Aus.*, XXXIV, 1910, 1–12, pls. I–XVII.

(XII) 1910. ———. "Description of a New and Extensive Area of Permo-Carboniferous Glacial Deposits in South Australia," *Trans. and Proc. Soc. S. Aus.*, XXXIV, 231–47, pls. XXXI–XLV.

VICTORIA

(XIII) 1890. Dunn, E. J. "The Glacial Conglomerates of Victoria," *Rep. Aus. Assoc. Adv. Science*, II, 452–58.

(XIV) 1892. ———. "Notes on the Glacial Conglomerate of Wild Duck Creek," *Dept. of Mines, Victoria, Special Reports*, pp. 5, pls. I–IV (photographs), with map and 2 sections.

(XV) 1893. Officer and Balfour. "Preliminary Account of the Glacial Deposits of Bacchus Marsh," *Proc. Roy. Soc. Victoria*, V, N.S. (May, 1893,) 45–68, pls. X–XII.

(XVI) 1893. Sweet and Brittlebank. "Glacial Deposits of the Bacchus Marsh District," *Rep. Aus. Assoc. Adv. Science*, V, 376–89, pls. XII–XIII (geological map and sections).

(XVII) 1895. Officer, Balfour, and Hogg. "The Glacial Geology of Coimadai," *Rep. Aus. Assoc. Adv. Science*, VI, 323–30, pls. XLIV–XLVII (photographs of striated bowlder and glaciated pavements).

(XVIII) 1896. David, Professor T. W. E. "Evidences of Glacial Action in Australia in Permo-Carboniferous Time," *Quar. Jour. Geol. Soc.*, London, LII, 289–301, fig. in text and pl. XII (striated bowlder and geological sections of the Bacchus Marsh glacial beds.

TASMANIA

(XIX) 1888. Johnston, R. M. *The Geology of Tasmania*. Government Printer, Hobart, Tasmania.

(XX) 189[illegible]. JOHNSTON, R. M. "The Glacier Epoch of Australasia," *Papers and Proc. Roy. Soc. Tasmania*, 105–7.

(XXI) 1002. KITSON, A. E. "On the Occurrence of Glacial Beds at Wynyard, near Table Cape, Tasmania," *Proc. Roy. Soc. [illegible]ia*, XV, N.S., 28–35, pl. III (Map of glacial beds).

(XXII) 1902. [illegible]E[illegible]ETREES, W. H. "Report of the Glacial Research Committee," *Rep. Aus. Assoc. Adv. Science*, IX, 191–94, pl. (two reproduced photographs of glaciated pebbles from Burnie and Table Cape, facing p. 192).

(XXIII) 1907. DAVID, PROFESSOR T. W. E. "The Permo-Carboniferous Glacial Beds at Wynyard, near Table Cape, Tasmania," *Rep. Aus. Assoc. Adv. Science*, XI, 274–79 (plate showing vertical section of glacial beds).

(XXIV) 1909. NOETLING, F. "Notes on the Glacial Beds of Freestone Bluff (Sandy Cove) near Wynyard," *Papers and Proc. Roy. Soc. Tasmania*, 157–69, pls. IX–XII (reproduced photographs of till beds).

NEW SOUTH WALES

(XXV) 1899. DAVID, PROFESSOR T. W. E. "Discovery of Glaciated Boulders at Base of Permo-Carboniferous System, Lochinvar, New South Wales," *Jour. and Proc. Roy. Soc. N.S.W.*, XXXIII, 154–59, pl. IV (reproduced photographs of two glaciated pebbles).

(XXVI) 1907. ———. "The Geology of the Hunter River Coal Measures, New South Wales," Part I, *General Geology, Department of Mines and Agriculture Mem. Geol. Survey of N.S.W.*, Geology No. 4, pp. 45–46, 124, 197, 199, 337 (pl. XXIV is a reproduced photograph of large granite bowlder, *in situ*, in till).

QUEENSLAND

(XXVII) 1892. JACK and ETHERIDGE. *Geology and Paleontology of Queensland and New Guinea.* Published under authority, Brisbane, I, 150–51.

WESTERN AUSTRALIA

(XXVIII) 1901. MAITLAND, A. G. *Annual Progress Report of the Geological Survey for the Year 1900*, 28, pls. III, IV (photographic reproduction of "fossiliferous glacial conglomerate," and four "glaciated boulders").

(XXIX) 1907. ———. "Presidential Address" (Section C), *Aus. Assoc. Adv. Science*, Report, XI, 146–49.

(XXX) 1910. Campbell, W. D. "The Irwin River Coalfield," *Western Australian Geological Survey, Bull. No. 38,* 39–43, pl. V (geological sections), and figs. 14–18 in text (photographic reproductions of bowlder beds and glaciated bowlders).

Pleistocene Glaciations

new south wales

(XXXI) 1885. Lendenfeld, R. von. *Report on the Results of His Recent Examination of the Central Part of the . . . . Australian Alps,* 1–16, pls. I–VI. Government Printer, Sydney.

(XXXII) 1885. ———. "The Glacial Period in Australia," *Proc. Linn. Soc. N.S.W.,* X, 44–53, pls. VII–VIII (two sketches of the Wilkinson Valley, Kosciusko).

(XXXIII) 1893. Helms, R. "On the Recently Observed Evidences of an Extensive Glacier Action at Mount Kosciusko Plateau," *Proc. Linn. Soc., N.S.W.,* XVIII, pr. 3, 349–64, pl. XVIII (map of the Snowy River district, showing the position of extinct glaciers).

(XXXIV) 1901. David, Helms, and Pittman. "Geological Notes on Kosciusko with Special Reference to Evidences of Glacial Action," *Proc. Linn. Soc. N.S.W.,* XXVI, 26–74, pls. III–X (sketch-plans of . . . . glaciated areas, vertical geological sections, and photographic views of *roches moutonnées* and glaciated bowlders).

(XXXV) 1908. David, Professor T. W. E. "Geological Notes on Kosciusko with Special Reference to Evidences of Glacial Action," Part II, *Proc. Linn. Soc. N.S.W.,* XXXIII, 657–68, pl. XXIII (view of the Upper Murray Valley).

tasmania

(XXXVI) 1893. Johnston, R. M. (See *ante* XX, pp. 92–102.)

(XXXVII) 1894. Dunn, E. J. "Glaciation of the Western Highlands of Tasmania," *Proc. Roy. Soc. Victoria,* VI, N.S., 133–38. Map.

(XXXVIII) 1894. Moore, T. B. "Discovery of Glaciation in the Vicinity of Mount Tyndall, in Tasmania," *Papers and Proc. Roy. Soc. Tasmania,* 147–49. Map.

(XXXIX) 1904. Gregory, Professor J. W. "The Glacial Geology of Tasmania," *Quar. Jour. Geol. Soc. London,* LX, 37–53, pls. VII–VIII (sketch-map of glaciated area around Mount Lyell and photographic views of Mount Owen. Also fig. in text, of a glaciated bowlder).

NEW ZEALAND

(XL) 1893. Hutton, F. W. "Report of Glacial Research Committee," *Rep. Aus. Assoc. Adv. Science*, V, 232–40 (map of existing and extinct glaciations).

(XLI) 1907. Marshall, P. "Report of Glacial Research Committee," *Rep. Aus. Assoc. Adv. Science*, XI, 283–85 (map showing extent of Pleistocene glaciations).

THE VALUE OF CERTAIN CRITERIA FOR THE DETERMINATION OF THE ORIGIN OF FOLIATED CRYSTALLINE ROCKS. I

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OUTLINE

INTRODUCTION
- Review of criteria which have been proposed for the determination of the origin of foliated rocks
- Scope of paper

TEXTURE AS A CRITERION FOR PRIMARY GNEISSES[1]
- Outline of discussion
- The distinction between igneous and metamorphic textures
- The significance of the elongated habit assumed by minerals when growing under certain conditions
  - Elongation of minerals under viscous conditions
  - Elongation of minerals on account of differential pressure
  - Conclusions regarding the causes of mineral elongation
  - Inferences from mineral elongation with regard to the texture of primary gneisses
- Conclusions regarding the texture of primary gneisses from the mode of their intrusion

USES OF ZIRCON AS A CRITERION FOR THE DETERMINATION OF THE ORIGIN OF FOLIATED ROCKS
- Introduction
- Identification of zircon
- The manner of its formation and its capacity for resisting alteration
- The significance of the presence or absence of zircon in a rock
- The significance of the character of the zircon grains
- Conclusions regarding the use of zircon as a criterion
- Use of other minerals similar to zircon

CHEMICAL COMPOSITION AS A CRITERION FOR THE DETERMINATION OF THE IGNEOUS OR SEDIMENTARY ORIGIN OF FOLIATED ROCKS
- Views of other writers
- The alteration of quartzite to sericite schist at Waterloo, Wis.
- The character of the chemical changes during the development of foliation
- Can chemical composition be used as a criterion for the determination of the origin of foliated rocks?

GENERAL SUMMARY

[1] By "primary gneiss" the writer understands a banded crystalline rock of igneous origin whose banding was produced prior to the complete solidification of the rock.

PART I

INTRODUCTION

REVIEW OF CRITERIA PROPOSED FOR THE DETERMINATION OF THE ORIGIN OF FOLIATED CRYSTALLINE ROCKS

Criteria constitute one of the most important divisions of a geologist's working "equipment." While they are needed and are being developed along the whole line of attack on the problems of geology, probably no section of investigators appreciates their value more than that engaged in unraveling the history of foliated crystalline rocks. This seems to be because that subject is particularly many-sided and difficult, for it cannot be said that suggestions as to methods of approach are at all lacking in number. To indicate the range of these proposals, and to give an idea of the state in which the problem stands today, the better known criteria for the determination of the origin of foliated rocks have been collected in the lists which follow. It must be acknowledged, however, that in many cases the results of their application are more suggestive than conclusive.

Criteria for the determination of original igneous or sedimentary character.—The following have been suggested as criteria for distinguishing foliated rocks which were originally sedimentary from those developed from igneous rocks:

Field evidence: *For igneous origin*—gradation into recognizable igneous rocks; preservation of original structures, such as boundaries of a dike; preservation of original textures, such as porphyritic; uniformity over large areas. *For sedimentary origin*—gradation into normal sedimentary rocks; preservation of original structures, such as pebbles of a conglomerate or cross-bedding; regular and continuous banding;[1] intercalation with beds of limestone or quartzite;[2] rusty weathering.[3]

Microscopic evidence: *For igneous origin*—preservation of igneous textures in the less altered portions; presence of minerals characteristically formed only from igneous melts and readily

[1] J. F. Kemp, "Pre-Cambrian Sediments in the Adirondacks," *Proc. Am. Assoc. Adv. Sci.*, XLIX (1900), 167.

[2] *Ibid.*, 174. [3] *Ibid.*, 168.

decomposed during sedimentation, such as nepheline,[1] leucite, etc.; presence of unaltered minerals characteristically formed only from igneous melts and which become modified or segregated during sedimentation, such as zircon and monazite; presence of secondary minerals generally considered to be more characteristic of altered igneous than altered sedimentary rocks, such as epidote, zoicite, chlorite, and hornblende.[2] *For sedimentary origin*—preservation of original fragmental texture;[3] presence of secondary minerals supposedly more characteristic of altered sedimentary than altered igneous rocks, e.g., a group high in Al_2O_3 and low in bases, such as staurolite, andalusite, sillimanite, and cyanite, but also other minerals as biotite, garnet, and graphite.

Chemical evidence: *For sedimentary origin*—variation from normal igneous rock types as shown by comparison with classified tables of igneous rocks arranged according to chemical composition; molecular ratio of Al_2O_3 to Na_2O, K_2O and CaO greater than 1; excess of K_2O over Na_2O by weight; excess of MgO over CaO by weight;[4] high Al_2O_3 content; high SiO_2 content.

Criteria for distinguishing primary gneisses from metamorphic rocks with a banded structure.—Many criteria have been suggested for the recognition of igneous rocks whose foliation was produced during the consolidation of the rock. The importance of this rock class has not been conceded by all geologists, though gneisses have been confidently described as such by Lawson,[5] Geikie and Teall,[6] Bonney,[7] Barlow,[8] McMahon,[9] Weinschenk,[10] Adams and Barlow,[11] and many others. Examples of primary gneisses have

[1] W. H. Emmons, "A Genetic Classification of Minerals," *Econ. Geol.*, III (1908), 620.

[2] C. R. Van Hise, "Treatise on Metamorphism," *U.S.G.S., Mono. XLVII* (1904), 916.

[3] F. Bascom, *Geol. Soc. Amer. Bull.*, XVI (1905), 294–95.

[4] E. S. Bastin, *Jour. Geol.*, XVII (1909), 445.

[5] A. C. Lawson, *Ann. Rep. Geol. Surv. Can.*, N.S. III, (1887), 139 f.

[6] A. Geikie and J. J. H. Teall, *Quar. Jour. Geol. Soc.*, L (1894), 645.

[7] T. G. Bonney, *Q.J. Geol. Soc.*, LII (1896), 17.

[8] A. E. Barlow, *Ann. Rep. Geol. Surv. Can.*, N.S., X, Part 1 (1897), 48–87.

[9] C. A. McMahon, *Geol. Mag.*, N.S., Decade 4, IV (1897), 345–55.

[10] E. Weinschenk, *Congrès géol. inter., compte rendu*, session VIII, I (1900), 326–40.

[11] F. D. Adams and A. E. Barlow, *Geol. Surv. Can.*, Mem. 6 (1910), 83.

most recently been described by Loughlin[1] in Connecticut and Rogers[2] in the state of New York. The following have been suggested as criteria for distinguishing these gneisses from those formed by the alteration of solid igneous rocks:

Field evidence: Banding in apophyses from the gneiss parallel to the walls and at an angle to the schistosity of the inclosing rock,[3] dikes of pegmatite belonging to the same magmatic series as the gneiss and either parallel to the gneissic structure and foliated with it or cutting the gneissic structure and undisturbed; lack of sharp contact between the acidic and more basic portions of the gneiss, indicating high temperature during the solidifications of the different bands;[4] presence of inclusions of foreign rock, which are but slightly deformed, in a matrix of well-banded gneiss;[5] presence of distinct bands of widely different composition, none of which may show evidence of shearing; flowlike curves of the banding, some of which may close in a circle.

Mineralogical evidence: Presence of minerals formed characteristically only from igneous melts and arranged in a manner impossible of formation from solid rocks by metamorphism, e.g., nepheline and olivine; textures due to crystallization from an igneous melt. Weinschenk[6] considers that epidote, garnet clinozoicite, sillimanite, and chlorite crystallize from the magma in the case of primary gneisses on account of the pressure present during the solidification of the rock, but the exact state of the rock during their formation is not definitely known.

SCOPE OF PAPER

In the following thesis only three of the many criteria which have been proposed have been considered. They are (1) the criterion of texture as applied to primary gneisses, (2) uses of zircon as a criterion, (3) use of chemical composition in the deter-

[1] G. F. Loughlin, *Am. Jour. Sci.*, 4th Ser., XXIX (1910), 447–56.

[2] G. S. Rogers, *Am. Jour. Sci.*, 4th Ser., XXXI (1911), 125–30.

[3] J. W. Gregory, *Q.J. Geol. Soc.*, L (1894), 265.

[4] *Geol. Surv. Can.*, Mem. 6 (1910), 83.

[5] *Geol. Mag.*, N.S., Decade 4, IV (1897), 354.

[6] *Congrès géol. inter., compte rendu*, session VIII, I (1900), 340.

mination of sedimentary or igneous origin. It must be remembered, however, that one type of criterion can seldom be employed effectively alone, although the limitation of possibilities obtained by the application of several criteria may lead to evidence that is practically conclusive.

The writer is deeply indebted to Dr. C. K. Leith and other members of the geological department of the University of Wisconsin for assistance and suggestions received during the preparation of this article.

TEXTURE AS A CRITERION FOR THE IDENTIFICATION OF PRIMARY GNEISSES

OUTLINE OF DISCUSSION

In order that the reader may more easily understand the trend of the argument which the writer will advance regarding the value of texture as a criterion for the identification of primary gneisses, the discussion which follows is here summarized.

Milch[1] in a recent article expresses the opinion that igneous rocks with an original foliation should not be included in the group of the "crystalline schists." He regards texture as the most promising criterion so far brought forward for distinguishing these rock classes. It is the suggestion that texture may be used as a criterion for distinguishing primary gneisses from those of metamorphic origin which the writer proposes to examine in the course of the present paper. Milch's idea was that "crystalline schists" are characterized by metamorphic or "crystalloblastic" texture, while gneissic rocks which possess an original foliation have the texture of igneous rocks. In order to get a clearer conception of the differences between these two varieties of texture, the writer will review the main features of metamorphic texture according to Grubenmann,[2] whose recent work marks a decided advance in the study of that subject. The causes underlying the differences between these two types of texture are apparently to be found in variations in conditions of crystallization; in one case solidification

[1] L. Milch, "Die heutigen Ansichten über Wesen und Enstehung der kristallinen Schiefer," *Geol. Rundschau*, I (1910), 49.

[2] U. Grubenmann, *Die kristallinen Schiefer*, I (1904), II (1907).

from a fluid and in the other recrystallization of a solid under differential pressure. Grubenmann considers that the chief expression of these different conditions of crystallization is to be found in the forms or outlines of the mineral constituents.

Unusual development of cleavage faces with consequent production of columnar or platy mineral forms is, according to Grubenmann, one of the most common characteristics of the minerals of "crystalline schists." Wishing to make use of this feature in a discussion of the texture of primary gneisses, the writer will review the causes of the unusual elongated habit assumed by minerals when growing under certain conditions. No mineral seems to exhibit better this capacity for abnormal form development than biotite which, happily also, is one of the most characteristic minerals of primary gneisses. The writer in the following discussion expresses the opinion that the biotite grains in normal igneous rocks are roughly equidimensional in shape, and that the platy forms present in metamorphic rocks and in primary gneisses are the result of crystallization under differential pressure. This would seem to suggest that the texture of primary gneisses must be intermediate between the igneous and the metamorphic types. Microscopic evidence seems to lead to the same conclusion. The writer, however, wishes to point out that from the very character of the intrusion of primary gneisses it is to be expected that granulation and recrystallization have frequently taken place after solidification and that, accordingly, a metamorphic texture cannot be regarded as proof that the banding in a gneiss was not produced when the rock mass was still partially fluid. It is the writer's view, however, that with certain limitations, igneous texture, when present, may be legitimately urged as proof of primary banding.

DISTINCTION BETWEEN IGNEOUS AND METAMORPHIC TEXTURES

By the term "texture" the writer understands the character of a thin section or surface of a rock due to its degree of crystallinity and to the size, shape, and arrangement of its minerals.

Crystalloblastic texture.—The term "crystalloblastic"[1] has been proposed as a designation for the texture of recrystallized rocks.

[1] F. Becke, *Tschermaks Min. petrog. Mitt.*, XXI (1902), 356–57.

Among the characteristics of this texture,[1] according to Grubenmann, are the following:

1. Lens-like and roundish forms of the minerals, well-developed crystal outlines not generally being present. When crystal forms do occur they are generally simple. Foliation of minerals is frequently developed.

2. The relative perfection of mineral form is dependent on the character of the minerals rather than upon their order of crystallization. The usual series of form development is as follows: titanite, rutile, hematite, ilmenite, garnet, tourmaline, staurolite, cyanite—epidote, zoicite—pyroxene, hornblende—magnesite, dolomite, albite, mica, chlorite, talc—calcite—quartz, plagioclase—orthoclase, microcline. In general the series is one of decreasing specific gravity or increasing molecular volume.

3. Marked development of crystal faces which are parallel to planes of mineral cleavage.

4. Characteristic mineral inclusions. In igneous rocks the inclusions are usually well-developed crystals which have solidified early. In the "crystalline schists" the later formed minerals may have more perfect outlines than their inclusions.

5. General absence of zones of different composition in minerals.

6. Holocrystalline character.

7. Tendency toward uniformity in size of grain.

Grubenmann's conception of the causes which underlie the differences in character between the textures of igneous and metamorphic rocks may be outlined as follows: He regards the forms of the minerals in igneous rocks as dependent largely on their order of crystallization, i.e., the earlier formed minerals have good crystal outlines while those of later development, having been compelled to occupy the remaining spaces, are irregular in form. In metamorphic rocks, on the other hand, he considers that the crystallization of all the minerals has been more or less hindered by the solid condition of the rock and that those minerals possess the best developed forms which have the strongest crystallizing force. This "force," Grubenmann regards as greatest in minerals which

[1] Grubenmann uses the word "Strukur" in place of "texture." "Strukur," as defined by him, relates to the form and size of the constituents. "Textur" is used for their arrangement.

have the smallest molecular volume or the highest specific gravity. As an explanation, also, for the unusual development of cleavage faces in certain minerals, he suggests that the molecular arrangement in such minerals is denser within the plane of mineral cleavage than across it. Though the suggestion of parallelism between perfection of crystal form and molecular density is interesting and probably significant, it must not be forgotten that the characteristics of crystalloblastic texture previously enumerated are based almost solely on observation.

Recent opinions on the crystallization of igneous rocks.—Several writers have recently questioned the views commonly held regarding the order of crystallization of igneous rocks. It has been suggested,[1] for example, that in the important class of the diabases the crystallization of the different minerals has been approximately simultaneous. In such cases it might be supposed that the relative development of crystal form was not entirely dependent upon the order of crystallization and that possibly the resulting texture might be confused with the metamorphic type. Thus in graphic granite,[2] where the outlines of the quartz areas agree more or less with the cleavage directions of the feldspars, the relations of the two minerals would seem to be dependent upon the individual properties of the minerals rather than upon their order of crystallization. Notwithstanding such cases of apparent simultaneous crystallization, it will probably be generally agreed that there is no reason yet known for thinking that order of crystallization is not the most important factor in determining the mineral outlines of normal igneous rocks. Grubenmann has pointed out, moreover, that there are important differences between the texture produced by simultaneous crystallization from an igneous melt and that resulting from recrystallization.

THE SIGNIFICANCE OF THE ELONGATED HABIT ASSUMED BY MINERALS WHEN GROWING UNDER CERTAIN CONDITIONS

The development of columnar or platy habit in minerals of a rock is a feature which is controlled by the individuality of the

[1] C. N. Fenner, "The Crystallization of a Basaltic Magma from the Standpoint of Physical Chemistry," *Am. Jour. Sci.*, XXIX (1910), 220.

[2] L. V. Pirsson, "Rocks and Rock Minerals" (1908), 212.

minerals and the conditions present during their formation rather than the relation of the minerals to their order of crystallization. According to the views previously outlined it should be, and actually is, a characteristic of metamorphic rocks rather than normal igneous varieties. As many minerals present in primary gneisses seem to possess an abnormal elongated habit, it is hoped that a discussion of this feature may throw some light on the texture and mode of origin of these rocks.

Elongation of minerals under viscous conditions in an igneous melt.—Pirsson[1] has recently published an interesting article in which the effect of viscosity on mineral habit is discussed. His observations on sections of rocks which have solidified quickly show that the minerals of such rocks tend to assume tabular or needle-like forms. It was especially noted that the elongation is generally parallel to prominent cleavage faces. Pirsson attributes this to the fact that the cohesive attraction within the plane of cleavage is greater than that across it. He supposes that viscosity may become so great that the molecular attraction across the mineral cleavage is insufficient to orient additional material so that the mineral becomes elongated in the direction of its cleavage. The growth of the crystal end, he considers, may be aided by the mobility imparted to the surrounding liquid by the heat of crystallization. Miers[2] has explained somewhat similar cases of elongation of crystals by the supersaturation of the surrounding solution. He considers that the end of the crystal may be able to remain continually in strongly supersaturated solution and, accordingly, grows more rapidly in one direction. This seems to be a somewhat different explanation from that given by Pirsson. While opinions regarding the cause of mineral elongation may vary, the fact that minerals do assume elongated habits when growing under viscous conditions in a magma and that the elongation takes place very frequently parallel to prominent cleavage directions seems to be pretty well established.

Elongation of minerals due to differential pressure.—That rocks which have recrystallized under great pressure are characterized

[1] L. V. Pirsson, "On an Artificial Lava-Flow and its Spherulitic Crystallization," *Am. Jour. Sci.*, XXX (1910), 97.

[2] H. A. Miers, *Science Progress*, II (1907), 128–29.

by a parallel arrangement of mineral constituents is, of course, a fact which is accepted by all writers. Perhaps, however, it is not so generally understood that the shapes of the so-called "platy minerals" of these rocks are generally different from those which the same minerals assume when growing under freer conditions. To illustrate this difference in shape, the writer will discuss the dimensions of quartz, biotite, hornblende, and feldspar in igneous and metamorphic rocks. These minerals were selected because they vary in the character of their cleavage and all are, moreover, common rock-forming constituents.

Quartz is the most common example of a group of minerals which possess no good cleavage. In metamorphic rocks it owes its form in the majority of cases either to granulation or recrystallization. When the grains result from granulation they are generally irregular in shape and roughly equidimensional, but the writer's observations seem to show that those grains which have crystallized[1] under differential pressure are frequently elongated parallel to the plane of rock cleavage. It appears, however, that the ratio of the dimension of the quartz grain in the direction of schistosity to that at right angles to it is seldom greater than two. Generally, also, as Leith[2] has pointed out, there is no relation between the elongation of quartz and its crystallographic directions.

Biotite is a mineral which is characterized by a single well-marked cleavage. Chlorite and sericite, both important rock-forming minerals, are similar to biotite in respect to cleavage. In the following measurements of biotite grains the ratio of the length in the direction of mineral cleavage to that across it has been determined. An average of 167 grains of biotite in 19 sections of igneous rocks showed a ratio of 1.5, but many soda-rich rocks gave average values of about 1.0, and in rocks with porphyritic texture the ratio rose sometimes to 2.0 or even 2.5. In the latter case the rocks have probably crystallized quickly and under somewhat viscous conditions. Similar measurements of biotites in sections of schists generally gave average values above 6, though when the development of schistosity had taken place near an igneous contact the

[1] The criteria for recognizing recrystallized minerals has been discussed by Leith in *U.S.G.S. Bull. 239* (1905), 70–71.

[2] *U.S.G.S. Bull. 239*, 35.

ratios were sometimes lower than this. An average of 46 observations on biotites of the Wissahickon[1] sedimentary gneiss gave a value of 7.2. In all schistose rocks so far mentioned the direction of mineral cleavage and elongation corresponded, in general, with the plane of rock cleavage. When biotites crystallize under mass-static conditions, i.e., in the absence of differential pressure, the form of the biotite grains, as shown in Fig. 4, seems to approach that characteristic of normal igneous rocks. In such cases there is commonly no relation between the direction of mineral elongation and that of rock cleavage. These "porphyritic" biotites may

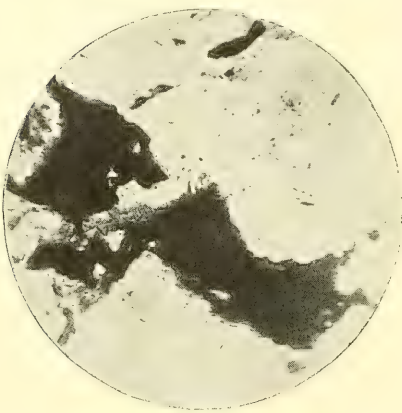

FIG. 1.—Biotites in nepheline syenite. ×32

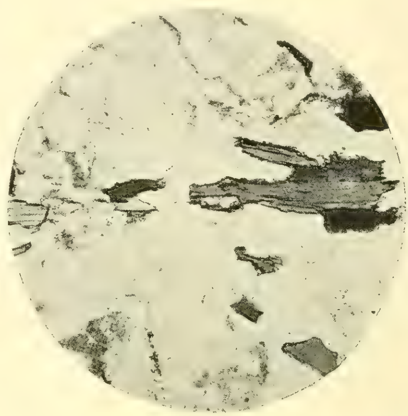

FIG. 2.—Biotites in primary gneiss. ×32

frequently be recognized by the number of inclusions they contain, a feature which is not common in grains which have crystallized under differential pressure. From the foregoing observations it may be seen that a platy form is not always characteristic of biotite, as is sometimes supposed, but that this habit is determined by the conditions of its formation. Such observations as the writer has made indicate that the effect of differential pressure on the forms of sericite and chlorite is analogous to that in the case of biotite.

Hornblende possesses a prismatic cleavage, the angle between the planes being about 124°. Leith[2] has shown that the hornblendes

[1] *U.S.G.S. Folio 162*, 1909.

[2] *U.S.G.S. Bull. 239*, 29.

in a schist are elongated parallel to the prism and that the elongation of the mineral corresponds generally with the direction of rock cleavage. In many cases the longer axes of the cross-sections of the hornblendes were observed to lie approximately in the plane of schistosity. According to Leith[1] the ratio of the greatest to least diameters of hornblende, which in schistose rocks varies from 100:20 to 100:24, ranges in igneous rocks from 100:30 to 100:75 with 100:40 as a common value.

Feldspar possesses various cleavages but those parallel to the base and the side pinacoid are the most pronounced. These two

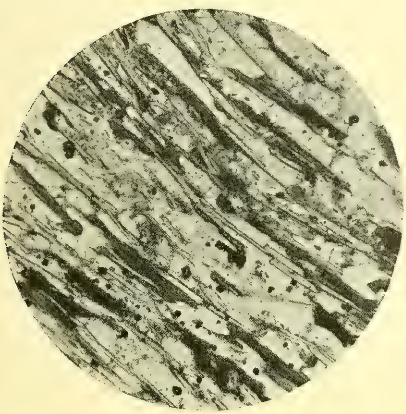

FIG. 3.—Biotites in schist. ×32

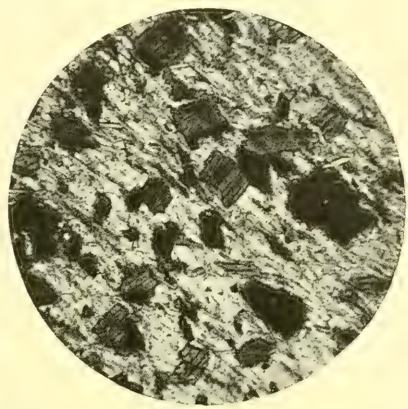

FIG. 4.—"Porphyritic" biotites in schist. ×32.

cleavages are approximately at right angles to one another. Leith[2] has stated that in schistose rocks the parallelism of the feldspar particles is not close and that rarely the parallel arrangement is also crystallographic. The writer's observations on similar rocks indicate that feldspar grains are occasionally elongated in the direction of rock cleavage but no relation was noticed between the elongation and the crystallographic directions of the grains.

Conclusions regarding the causes of mineral elongation.—It has been noted that under certain conditions minerals tend to assume an abnormal elongated habit. High viscosity or strong super-

[1] *Op. cit.*, 30–31.

[2] *Op. cit.*, 40.

saturation and differential pressure appear to be the most important of these conditions. In either of these cases the resulting form of the mineral seems to depend to a marked degree upon the character of its cleavage. The elongation of quartz, on the other hand, a mineral which possesses no good cleavage, is, under differential pressure at least, not marked and is apparently independent of crystallographic directions. The only possible exception noted to these generalizations is feldspar. While feldspars crystallized from viscous melts are, apparently, elongated parallel to the two principal cleavages, in the grains formed under differential pressure there does not appear to be any relation between the direction of elongation and the position of mineral cleavage. This is possibly to be explained by the number of cleavage planes in that mineral or to the position of the two principal cleavages at right angles to each other.

Pirsson[1] has explained the development of mineral elongation in viscous melts by differences in molecular attraction which are considered to exist between directions within and across the cleavage. Since the same forces act during the normal crystallization of minerals, this might lead one to think that the elongation of crystals due to the conditions of the solution or to differential pressure represented only a more pronounced development of differences in dimensions existing in crystals of normal development. That this is not so, and that the elongation of minerals which have developed under favorable conditions may be independent of mineral cleavage is shown by the well-known prismatic crystals of quartz, found so frequently in cavities, notwithstanding the fact that quartz is a mineral which possesses no good cleavage. It seems a more general rule that uniaxial minerals, when freely developed, are elongated in the direction of the vertical axis, no matter what the direction of mineral cleavage. Apatite, beryl, and corundum, for example, appear to be all normally elongated at right angles to their best plane of cleavage. The same is true for the orthorhombic minerals topaz and danburite. Among rocks, pegmatites probably offer the most favorable conditions for the development of biotite crystals and here they are frequently, if not generally, elongated at right angles to their cleavage.

[1] *Am. Jour. Sci.*, XXX (1910), 110.

To the writer, the conception of differences in molecular attraction within and across the cleavage of a mineral seems to afford a plausible explanation why the elongation of minerals under unfavorable conditions for growth takes place parallel to the plane of mineral cleavage. This idea, though, is of course purely speculative. There may be also reasons, not at present known, which would cause minerals, such as biotite, to be more stable under conditions of differential pressure when lying with their planes of cleavage parallel to the greatest pressure. It is almost useless to conjecture what causes the normal elongation of some minerals at right angles to their cleavage, though one might suggest molecular form or arrangement as possibilities.

Inferences regarding the texture of primary gneisses from mineral elongation.—Descriptions of primary gneisses seem to show that a more or less parallel arrangement of platy mineral constituents is a constant characteristic of this rock type. This arrangement may be considered to have been caused by (1) rotation of minerals in a still fluid magma, by (2) development of abnormal elongated mineral forms during crystallization, by (3) parallel growth of minerals with normal form development, or by (4) granulation, slicing, or gliding. The first method would probably give rise to characteristic igneous textures. Microscopic studies of schists indicate that the last three processes would tend to the production of the metamorphic type of texture.

The writer has endeavored to point out in preceding sections that the development of abnormal elongated mineral forms is an important feature in the production of schistosity in metamorphic rocks. The following review of the most abundant minerals of primary gneisses is intended to show that this process is also a leading one in the crystallization of primary gneisses and, accordingly, that the texture of such rocks must have some of the characteristics of the metamorphic type.

Among the minerals most frequently mentioned as having been rotated in a magma is *biotite*.[1] The following points seem to indicate, however, that in the case of this mineral rotation must be of secondary importance and that its orientation is largely due to the

[1] E.g., *Geol. Mag.*, N.S. (Decade 4), IV (1897), 348.

growth of unusually elongated grains parallel to the direction of least pressure.

1. The measurements previously given indicate that biotites which have crystallized slowly from igneous melts are not platy in the majority of cases, and that before being interfered in crystallization by other minerals they were not far from cubical in form. The orientation of such grains in a fluid magma must then be almost impossible.

2. The extremely irregular outlines of biotites in normal igneous rocks suggest that biotites do not generally crystallize much in advance of the quartz and the feldspar so that completely formed biotite grains cannot be considered to have been ever floating loosely in a fluid magma.

3. Measurements made of biotite grains in a gneiss, which is considered by the writer from field evidences to possess original banding, gave values of from 2.5 to 5.0 for the ratio of the length in the direction of mineral cleavage to that across it. As similar tests on igneous rocks usually gave values from 1 to 1.7 it can be seen that the elongation of biotite is in this case decidedly greater than that characteristic of deep-seated igneous rocks which have solidified under quiet conditions.

4. There seems no reason to think that the biotites of primary gneisses have crystallized under viscous or strongly supersaturated conditions since such rocks are generally of deep-seated origin and probably contained abundant water when in the fluid state.

Elongated *feldspar* grains have been described as having been formed during original crystallization in the Twilight[1] gneissoid granite of Colorado. In this rock the feldspars in the more foliated portions occur as elongated anhedra, while in places where the rock is more massive they possess crystal outlines. In the former case the direction of elongation seems to be unrelated to the crystallographic directions of the mineral.

The elongation of *quartz* has also been observed by the writer in thin sections of the biotite gneiss previously mentioned as exhibiting primary banding.

One who grants that pressure can be sufficiently active during

[1] W. Cross, E. Howe, J. D. Irving, W. H. Emmons, *U.S.G.S. Folio 131* (1905), 7.

the crystallization of primary gneisses so as to cause the development of elongated forms in the minerals must also expect to find in the texture of these rocks many other features common to the metamorphic type. It must be supposed, for example, that along with marked development of cleavage faces would be a general tendency toward the series of form development characteristic of "crystalline schists" as outlined by Grubenmann. The writer's observations seem to corroborate this. In short, the texture of primary gneisses appears to be intermediate between the igneous and the metamorphic types, being more like the latter according as the movements producing the banding continued late in the period of consolidation.

CONCLUSIONS REGARDING THE TEXTURE OF PRIMARY GNEISSES FROM THE MODE OF THEIR INTRUSION

Various types of rock bodies have been described as possessing an original banding and it is natural to suppose that the methods of their intrusion must differ considerably. The size of the bodies varies from dikes, such as are characterized by parallel feldspar phenocrysts, to masses of batholithic proportions. In the case of many of such dikes it can hardly be doubted that the foliation was produced by movements in the magma since the rocks cut by the dikes sometimes show no evidence of rock flowage. The origin of the banding of the gneiss in certain batholiths, attributed by Lawson and others to movements prior to the complete solidification of the rock seems, however, to be considered more uncertain by many geologists. The identification of this type is, however, more important than that of the smaller bodies and its origin will be considered more fully.

The association of igneous activity and batholithic intrusion with periods of mountain building[1] is well recognized. Those who have described batholithic masses as possessing a primary banding are in general agreement that at the time of the intrusion crustal deformations were active and continued so during the solidification of the igneous mass. The intruded rocks have generally been considered to have undergone rock flowage, and, accordingly, no

[1] R. A. Daly, *Am. Jour. Sci.*, 4th Ser., XXII (1906), 195–216.

matter what the depth, to have been under considerable pressure. Weinschenk has more than any other emphasized the importance of pressure during the intrusion of primary gneisses and suggests as proof the wide schistose zones about such bodies. As showing that these were formed during the intrusion, he states[1] that the schistosity of the contact rocks is generally parallel to the border of the batholith and that tourmaline needles, which he considers were formed by pneumatolitic action, frequently lie across the the plane of foliation and, accordingly, were formed later than the schistosity.

It seems not illogical to assume that the movements which were, apparently, present late in the period of consolidation should have sometimes continued after portions or the whole of the rock had completely solidified. If such were the case there would result considerable recrystallization and granulation so that typical crystalloblastic or cataclastic textures might be superimposed on that resulting from primary consolidation. It follows that the mere presence of a metamorphic texture is no proof that the banding of a gneiss is not of primary origin. When, however, such rocks are characterized by true igneous texture, as would be the case if the movements ceased early in the period of consolidation, there seems no reason why this feature should not be regarded as proof that the banding was of primary origin. The use of texture as a criterion for the identification of primary gneisses seems on the whole, then, to be of only limited application.

THE USE OF ZIRCON AS A CRITERION FOR THE IDENTIFICATION OF THE ORIGIN OF FOLIATED ROCKS

INTRODUCTION

It was noted in the general introduction that the criteria which have been proposed for determining the igneous or sedimentary origin of metamorphic rocks can seldom be employed decisively. This is largely because the evidence used is generally indirect, and its application as proof of original character is frequently dependent upon inferences which have as yet not been shown to be correct.

[1] *Congrès géol. inter., compte rendu*, session VIII, I (1900), 330, 337.

The criterion of chemical composition, for example, has been especially popular, probably because it permits of mathematical expression and is almost free from what is called "the personal equation." Its use, however, is based on a supposition, it being assumed that a rock as a whole undergoes no significant chemical change during the development of foliation.

The use of zircon, on the other hand, is especially attractive since it deals with first-hand evidence, and while its limitations are not yet fully defined they can be determined with no great effort by laboratory research. In brief, the proposal regarding the use of this mineral as a criterion for the determination of the origin of foliated rocks is based on observations which show that zircon is present in nearly all igneous rocks as minute crystals and that it is practically absent from argillaceous sediments, having been concentrated during sedimentation in the arenaceous deposits. During this process, also, the zircons tend to assume a worn and rounded appearance.

Derby[1] was the first to appreciate the possibilities of zircon as a criterion, his article outlining the suggestion appearing in 1891. The method does not seem, however, to have been taken up by many geologists, probably more through a lack of advertisement than from any inherent difficulty or weakness. Important use has been made of zircon and the somewhat similarly occurring minerals monazite and xenotime by Derby and his co-workers during active fieldwork in Brazil.[2]

On considering the possibilities of zircon as a criterion, one naturally thinks of such questions as the following: Is the *presence or absence* of zircon sufficiently characteristic of certain rock classes, such as igneous or sedimentary, so that it can be used as a criterion for their recognition after alteration? Is the *character* of the zircon grains in different rocks sufficiently distinctive in order that it may serve to identify them? Do zircon grains ever form or recrystallize during the development of foliation?

[1] C. A. Derby, *Proc. Rochester Acad. Sci.*, I (1891), 202.

[2] It was from Dr. Leith, who has recently had the opportunity of observing the methods of the Brazilian geologists, that the writer received the suggestion to investigate this subject.

Since the answers to the first two questions involve a knowledge of the stability of zircon the third will be considered first. Preceding this, however, a short review will be given of the methods used in the identification of this mineral.

IDENTIFICATION OF ZIRCON

Separation from other constituents.—While zircon is very widely distributed in rocks, it is not usually present at any time in more than minute quantities, indeed generally under 0.4 per cent. For study, accordingly, the zircons in a rock must be concentrated in some way. Derby[1] has recommended that the grains be separated from the ground powder by washing in a Brazilian miner's pan, which, as described, should be made of thick sheet copper in the shape of a broad cone, with sides meeting at the apex at an angle of 120°. Twelve inches is suggested as a suitable diameter of the pan at the opening. The residues obtained, Derby states, may be further separated, when necessary, by means of heavy solutions as Thoulet's or Klein's or with the electromagnet. H. Thürach,[2] in carrying out a valuable and extensive series of tests for the purpose of determining the distribution of zircon, anatase, brookite, pseudobrookite, and other minerals, employed a porcelain dish instead of a copper pan. The writer has examined a considerable number of rocks in the way recommended by Derby and found the method very satisfactory. It was considered advisable to pass the powder through a sieve before panning. The screen generally used was one of 60 mesh. In each case a sample of the concentrate was mounted in Canada balsam similarly to a rock section.

Identification.—The work of Thürach and Derby has shown that minute grains of zircon can usually be easily and surely distinguished from all other minerals except xenotime and cassiterite by ordinary optical methods. The following summary of the characteristics of zircon, except when otherwise stated, has been taken from the work of Thürach.

1. Crystal form.—Rounded grains and well-developed crystals of the tetragonal system. The crystals are usually bounded by

[1] *Proc. Rochester Acad. Sci.*, I (1891), 198.

[2] Würzburg, *Phys.-Medic. Gesellsch.*, XVIII (1884).

some combination of prismatic and pyramidal faces, the former, however, being almost always present. In Fig. 8, representing zircons of the Butte granite, basal pinacoids may be recognized but this, apparently, is not a common development. It was noted by the writer that the cross-sections of zircons are generally oblong rather than square.

2. Twinning.—Twinning in microscopic grains has never been with certainty recognized by Thürach. The writer's experience has been similar. Geniculated twins were observed by Derby in the granite from Somerville, Me.

3. Zonal banding.—Frequent.

4. Color.—In fresh crystalline rocks almost always colorless. The writer has observed grains considered to be zircon which were slightly brownish.

5. Optical characters.—High refringence. Brilliant interference colors of high order, usually red and green, less commonly yellow or blue.

6. Inclusions.—Numerous. Considered by Thürach to consist of apatite, fluids, or gases. Derby states that xenotime also exists as inclusions.

Rutile has been mistaken for zircon but can be distinguished by its color (yellow, yellowish or reddish brown), pleochroism, twinning (common), absence of inclusions, and chemical reactions.

Xenotime was not described by Thürach. From the observations of Derby[1] the usual crystal form appears to be octahedral. It may be identified by the erbium line in the spectroscope or by chemical means.

The writer has not observed cassiterite in microscopic crystals. It is undoubtedly much more limited in its distribution than zircon but when present may be difficult to distinguish from the latter. According to Lacroix[2] cassiterite is more frequently twinned than zircon. It is also generally darker in color. Gaubert[3] states that it can readily be distinguished from zircon by color reactions with organic substances.

[1] *Mineralogical Mag.*, XI (1897), 304–10.

[2] A. Lacroix, *Minér. de la France*, III (1909), 207.

[3] Paul Gaubert, *Bull. soc. fran. minér.*, XXXIII (1910), 326.

THE FORMATION OF ZIRCON AND ITS CAPACITY FOR RESISTING ALTERATION

Crystallization from a magma.—Microscopic evidence shows beyond any doubt that the minute zircons (they are rarely over 0.5 mm. in length) which seem to occur in nearly every igneous rock have in general crystallized as an original constituent. Moreover such methods as are in use for determining the order of crystallization of minerals indicate that zircons have usually formed very early in the consolidation of the magma.

Formation in rocks secondarily through the agency of water or gases.—Derby[1] was of the opinion that all zircons in rocks have resulted from the crystallization of igneous melts and that they could not be formed in a rock secondarily. He argues: "Unless, therefore, these rare chemical agents are introduced into the mass subject to metamorphism by the action of the so-called mineralizing agents (as fluorine, boron, and tin are supposed to be in the formation of tourmaline, topaz, and cassiterite), it is difficult to conceive how the minerals in question can appear as newly formed elements in a metamorphosed sedimentary. Their early crystallization and uniform distribution in eruptives, as well as their absence from schists metamorphosed by contact (in the rare cases in which zircon has been noticed it may be presumed to have existed in the original sediment) exclude the hypothesis of such an introduction."

Thürach, on the other hand, was of the opinion that zircons could form from watery solutions and cited as proof the zircons which occur in druses in the chlorite schist of Tyrol and also the well-developed crystals in the sericite schist of Taunus which is associated with a quartzite containing well-rounded grains. There is just a possibility, however, that in the latter case the sericite schist may have been formed from material which was not as well sorted as the underlying quartzite and consequently more easily rendered schistose. In such a case one would not expect the zircons to be as water-worn as in the purer variety.

The following two cases which have recently come to the writer's attention furnish additional proof that the views expressed by Derby must be considerably modified. In the crystalline lime-

[1] *Proc. Rochester Acad. Sci.*, I (1891), 203.

stone of Grenville,[1] Ont., large crystals of zircon with well-developed faces have been found. They are associated with graphite, wollastonite and titanite and were probably formed through the action of intrusives. The evidence here seems to show that zirconium is capable of being carried in solution some distance from the main body of the intrusive.

At Rib Hill, Wausau, Wis., there is a quartzite which is cut by granite and which contains abundant zircons, many of which exhibit

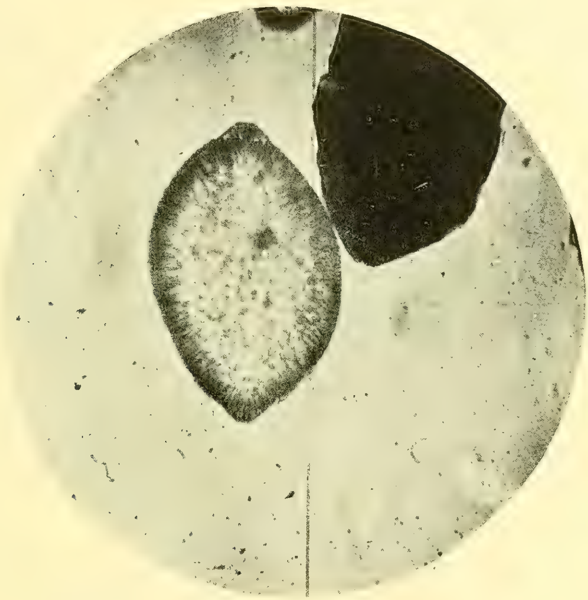

FIG. 5.—Secondary enlargement of zircon. ×180

secondary enlargement. A microphotograph of one of these grains is shown in Fig. 5. The new material has been added largely to the ends of the grains, usually forming pyramidal faces terminated by the basal pinacoid, though the latter is sometimes absent. In one case the new growth was observed to completely envelop the original grain. This suggests that the material for the later crystallization was, in part at least, introduced from without and field relations seem to point to the granite as the source.

[1] C. Hoffmann, *Ann. Rep. Geol. Surv. Can.*, IV, N.S. (1890), 66T.

The capacity of zircon to resist alteration.—To one who cannot see any virtue in the use of zircon as a criterion, if this mineral can be formed in a rock secondarily, the evidence given in the last section must certainly be disappointing. If the reader, however, is willing to accept a compromise and appreciate the value of a mineral as a criterion which is markedly characteristic of certain rock types, widely distributed, and which remains practically unaltered in a rock long after the commoner constituents have

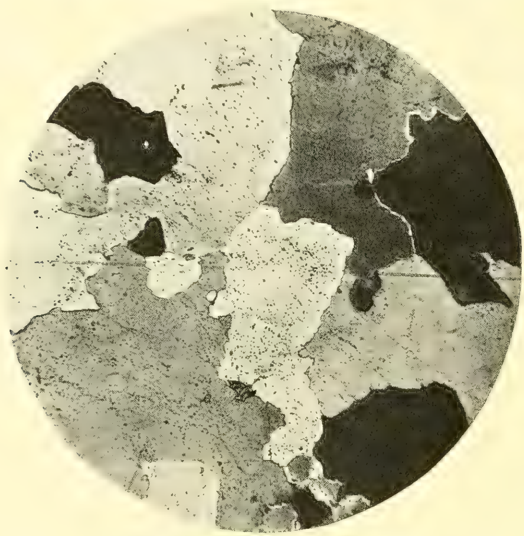

FIG. 6.—Rib Hill quartzite. Crossed nicols. ×20

entirely recrystallized perhaps there is no reason why he should not regard the method as one of distinct promise.

To illustrate: Take the case of the Wausau quartzite which contained the zircons with secondary enlargement. The quartz has here undergone such extreme recrystallization that ordinary evidence of clastic texture has been entirely destroyed. The rock, indeed, is almost as vitreous as ordinary vein quartz. A microphotograph of a section of this rock is shown in Fig. 6. Fig. 7 represents zircons taken from the same specimen as the slide illustrated in Fig. 6 and shows their round and well-worn appearance, a feature which, as will be seen later, is more or less character-

istic of the zircons in sedimentary rocks. Fig. 7, indeed, shows that, notwithstanding the cases of secondary enlargement, the zircons in this rock have suffered but little alteration.

Other tests made by the writer seem to confirm the view that zircon is remarkably stable under the conditions present during the development of foliation. Three sericite schists, for example, considered to have been developed from quartzite all showed no change in the character of the zircons during the alteration of the

FIG. 7.—Zircon grains from Rib Hill quartzite. ×40

rock. In two of these cases the zircons of both fresh and altered rocks were roundish in form while in the third (illustrated in Figs. 10 and 11) they were somewhat better developed. Two quartzose phases of highly altered sedimentary gneisses showed abundant and well-rounded zircons. In two cases of schist developed from igneous rocks the zircons in the schists were similar to those in the unaltered rocks and possessed sharp crystal outlines.

THE SIGNIFICANCE OF THE PRESENCE OR ABSENCE OF ZIRCON IN A ROCK

Distribution of zircon in unaltered rocks.—Leaving aside for the moment the question of the stability of zircon, one may inquire

regarding the distribution of zircon in unaltered rocks for this, indeed, must form the basis for the application of zircon as a criterion.

Thürach stated that he had recognized zircons in every igneous rock tested, including basalts and dolerites. His observations indicate, however, that they are most abundant in the acidic types such as granite and syenite. Derby, also, has expressed the opinion that zircons are almost universally present in eruptives. Zircons were recognized by the writer in every granitic rock examined but their abundance was found to vary greatly with specimens from different localities. They appeared to be much less numerous in basalts and other basic rocks than in the acidic varieties, none, for example, being detected in a test on material from a specimen of diabase from Gowganda, Ont.

Zircon appears to be present in varying amounts in practically every *arenaceous* rock. Thürach reported its presence in every sandstone examined and the writer's observations are similar, eight quartzites all showing zircon and generally abundant.

Shales, however, appear to be comparatively free from zircon though Thürach's thorough tests revealed its presence in nearly every case examined. Derby says that zircon is almost absent from argillaceous deposits and they were only observed occasionally in such rocks by the writer.

Distribution of zircons in metamorphic rocks.—Thürach found zircon to be generally abundant in feldspar-rich gneisses (presumably largely of igneous origin) and less common in, but seldom absent from, mica gneisses (probably mostly of sedimentary origin). Derby's observations show that schists free from quartz such as amphibolite and amphibole schist frequently show abundant zircons but that micaceous schists contain only comparatively few grains of that mineral. The writer's observations, as was mentioned before, indicate that zircons undergo but little change during the development of foliation in a rock.

On the whole, then, it appears that the examination of metamorphic rocks does not reveal any differences in distribution of zircon than might be expected from the preservation of original grains.

Conclusions.—The facts at hand seem to show that when zircon is present in a rock in considerable abundance the original rock was probably either igneous or a sandstone and not an argillaceous rock or a chemical deposit.

The absence of zircon in a rock is not so significant. It, however, favors the idea that the original rock was of sedimentary origin and suggests somewhat strongly that it was not a granitic rock or a sandstone.

THE SIGNIFICANCE OF THE CHARACTER OF THE ZIRCON GRAINS IN FOLIATED ROCKS

The rounding of the crystal outlines during sedimentation.—It has been previously noted in a general way that the zircon grains in igneous rocks have well-developed crystal outlines while those in sedimentary rocks are more or less rounded. The facts of observation should, however, be stated more fully in order that the amount of confidence to be placed in this distinction as a criterion can be determined.

Thürach has stated that the zircons in granites and syenites generally show well-developed crystal forms while many roundish grains occur in diorite. In basalts and dolerites he observed that the zircons were generally roundish and frequently showed a zonal banding parallel to the boundaries of the grain. In sedimentary rocks, according to Thürach, the zircons are generally rounded but some possess distinct crystal boundaries.

While Derby has noted that the crystal forms in igneous rocks are, as a rule, better developed than those occurring in sands, he has expressed the opinion that in the former perfectly sharp-angled crystals are the exception rather than the rule and apparently characterize the amphibolitic rather than the micaceous types.

The investigations of Mackie[1] on the rounding of sand grains indicate that zircon is more readily rounded than quartz, probably on account of its higher specific gravity. Four sands discussed by this writer showed a predominance of rounded forms in each case.

[1] Wm. Mackie, *Trans. Edinburgh Geol. Soc.*, VII (1897), 298–311.

The recent article by Scherzer[1] on the recognition of the types of sand grains is interesting in this connection. Scherzer considers that well-rounded grains are typical of eolian deposits. In this paper reference is made to the experiments of Daubrée which seemed to show that granules less than 0.1 mm. in diameter[2] cannot be rounded by water action. Typically rounded grains of zircon were observed by the writer in the section of zircons illustrated in Fig. 9 under .06 mm. in diameter.

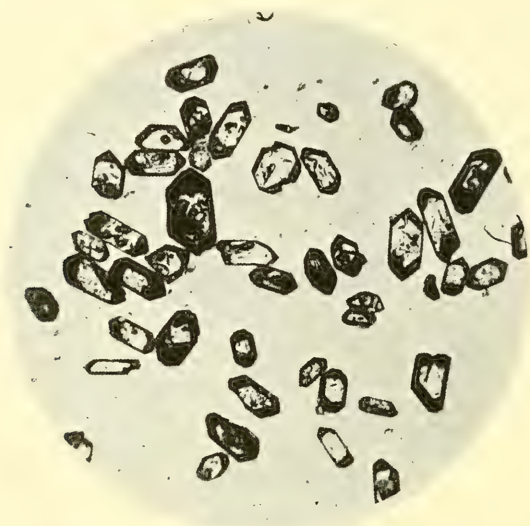

FIG. 8.—Zircons from Butte granite. ×40

The writer's tests indicate that the zircons of granitic rocks have generally good crystal form, sometimes with perfect faces as shown in Fig. 8 and in other cases having somewhat rounded outlines. The zircons represented in Fig. 8 are, by the way, from a biotite granite and form an exception to the rule proposed by Derby with regard to the relative perfection of form between the amphibolitic and micaceous types. Tests made on about 15 specimens of

[1] W. H. Sherzer, *Bull. Geol. Soc. Amer.*, XXI (1910), 625–62.

[2] V. Ziegler in an article which has just appeared states that it is improbable that grains less than 0.75 mm. in diameter could be well rounded under water (*Jour. Geol.*, XIX [1911], 654).

rocks derived from sand showed that the zircons were generally more rounded than is usual in igneous rocks.

From a consideration of the above facts, it must be acknowledged that the zircons in igneous rocks are sometimes roundish in character and that in sedimentary rocks, if the original materials were not subjected for considerable time to the abrasive and sorting action of rivers, waves, and wind, perfect crystal forms may have been preserved. Notwithstanding these possibilities it seems safe

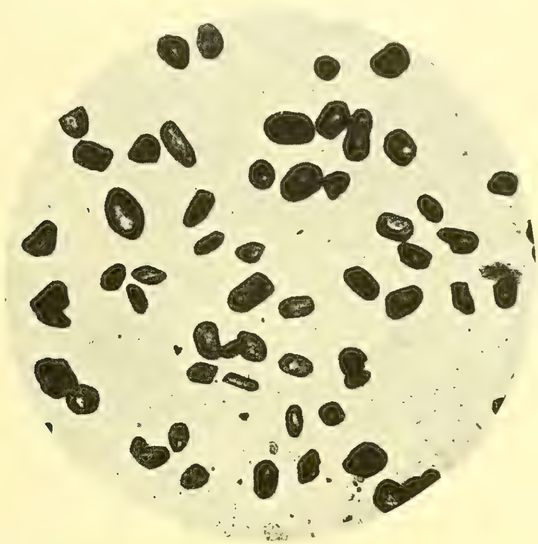

FIG. 9.—Zircons from quartzite, Gowganda, Ont. ×40

to say that the presence of good crystal outlines in zircons of a foliated rock indicates that the original rock was probably igneous while rounded forms suggest a sedimentary origin. When the rounding is pronounced the proof of sedimentary character is strong, but when it is slightly developed it is of little significance.

The luster of zircons in igneous and sedimentary rocks.—The luster of zircon grains is a character closely allied to their form. According to the writer's observations the zircons in igneous rocks usually have a clear, fresh, vitreous appearance while those in sedimentary rocks frequently have a dull, pitted look like ground

glass. Derby[1] has noted this distinction and remarked that "a lack-luster aspect without evidence of alteration is the most certain sign of wear." This dull appearance of the grains is brought out fairly well in Fig. 7.

While it is true that a fresh appearance, like good crystal form, may be preserved during sedimentation, the writer regards this feature as of considerable value as an additional proof of igneous or sedimentary origin.

The significance of peculiar crystal forms.—The zircons in many rocks possess distinct individuality in their forms and the writer considers this peculiarity may be made use of in determining the origin of foliated rocks. It sometimes happens, for example, that near an area of schistose rocks there are other rocks of less altered character which, according to field relations, might well represent part of the original rock, now largely schistose. It is the writer's opinion that zircons in the fresh and altered rocks might be so similar in character as to be fairly conclusive evidence that the two rocks were originally of the same character.

The variation in form depends largely upon the relative development of the different possible faces. Sometimes the zircons are needle-like in character with the prismatic faces prominent, and at other times the crystals may be short and terminated by one or more sets of pyramids. The basal pinacoid face seems to be only rarely developed[2] but is present in the majority of grains in the section made from the Butte granite and illustrated in Fig. 8.

This use of peculiar crystal forms has been tested by the writer successfully in several cases where the fresh and unaltered representatives of a rock were obtainable.

CONCLUSIONS REGARDING THE USES OF ZIRCON AS A CRITERION

1. The presence of abundant, minute grains of zircon in a metamorphosed rock strongly indicates that the original rock was either igneous or an arenaceous sediment. A recomposed igneous rock could in no way, of course, be distinguished from an igneous one by means of this mineral. The possibility of introduction from

[1] *Proc. Rochester Acad. Sci.*, I (1891), 202.

[2] J. D. Dana, *Descriptive Mineralogy* (1909), 483.

igneous contacts must also be kept in mind, though, as was stated, cases where minute zircons have been clearly introduced at contacts are not known.

2. Abundant grains of well-crystallized zircon, especially when uniform in character and fresh in appearance indicates that the original rock was igneous. There are, however, the possibilities of recrystallization of the zircons in an arenaceous sediment during dynamic metamorphism, introduction near igneous contacts and preservation of crystal form during sedimentation.

3. Abundant grains of well-rounded zircon, especially when possessing a worn appearance like ground glass strongly indicates a sedimentary origin. Zircons, however, occur quite frequently as roundish grains in igneous rocks, being especially common in the more basic types.

4. Absence of zircon grains in quartzose bands in a metamorphic rock indicates that such bands do not represent sedimentary layers but were probably deposited from solution.

5. Similarity in character of zircon grains may be used in identifying the unaltered equivalent, when such exists, of the metamorphic rock. Derby has employed this method in Brazil in mapping the distribution of badly weathered rocks.

THE USE OF MONAZITE AND XENOTIME AS CRITERIA FOR DETERMINING THE ORIGINAL CHARACTER OF FOLIATED ROCKS

Monazite (Ce, La, Di), PO_4, has been mentioned by Derby as possibly having an application similar to zircon in the determination of the igneous or sedimentary origin of schists and gneisses. Derby[1] has discussed various methods for the identification of monazite in minute grains. In addition to ordinary microscopic tests, microchemical reactions and examination with a hand spectroscope are recommended. Monazite, according to Derby, is almost universally present in muscovite granites and their gneissic equivalents and frequently occurs in biotite granites. Tests so far made by him indicate that it is lacking in the amphibole granites and all other more basic rocks. As in the case of zircon, monazite becomes concentrated in the arenaceous deposits during sedimentation. The

[1] *Am. Jour. Sci.*, 4th Ser., X (1900), 217–21.

value of monazite as a criterion is, however, lessened by the fact that several cases have been observed in which it is clearly secondary in a metamorphic rock. In addition to secondary enlargements of rounded grains, Derby has noted clear crystals containing inclusions of hematite and rutile and, accordingly, almost certainly of secondary origin. Perhaps the chief application of monazite in the indentification of metamorphic rocks will be found in its use as an aid in the recognition of the unaltered phase of a metamorphic rock when the original type still exists.

Xenotime, YPO_4, is somewhat similar in its character and occurrence to xenotime. It has, however, even a more limited distribution than the latter.

[*To be continued*]

SILICEOUS OÖLITES AND OTHER CONCRETIONARY STRUCTURES IN THE VICINITY OF STATE COLLEGE, PENNSYLVANIA[1]

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The Pennsylvania State College

The town of State College is situated near the geographical center of Pennsylvania. It lies among the erosion remnants of the Appalachian Mountain system and near the western border, where the highly folded strata of the Tussey and Bald Eagle ranges begin to flatten out into the gently dipping beds of the Allegheny Mountains. These mountains occupy the synclines of the original folds

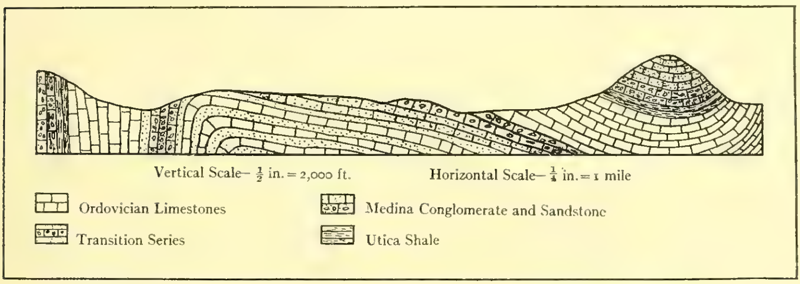

FIG. 1.—Representative geological section through the oölitic area

while the present valleys always lie along the original anticlines, which have suffered more rapid erosion than the synclines, permitting the streams to cut down to the base of the Ordovician system.

A geological section through the area would show, from the oldest exposed strata upward, several hundred feet of interbedded sandstone, limestone, and calcareous sandstone, grading over in the upper layers into limestone-conglomerate in which the pebbles

[1] Paper read before Section C of the British Association for the Advancement of Science, Portsmouth meeting, 1911. The discussion showed that siliceous oölites are plentiful in England in rocks of similar physical character and geological age, but such satisfactory evidence of their origin by replacement of calcareous oölites had not been previously found.

have not as a rule suffered extensive erosion. Few fossils have so far been found in the lower portion of this series and only a few distinct gastropods in the upper portion. There are, therefore, differences of opinion regarding the geological age of this series but it should probably be regarded as a transition stage between the Cambrian and the Ordovician.

Above this transition series, which is exposed only in the eroded crests of the anticlines, there are several thousands of feet of fossiliferous limestones which may be regarded as typically Ordovician and these are overlain by about five hundred feet of Utica shale of the Upper Ordovician. Following the shale are the Medina conglomerate and sandstone, which occupy the synclines of the original folds and cap the present mountains.

THE TRANSITION SERIES

The greatest interest in this area centers around the transition series. It shows very frequent alternations of dark, crystalline, magnesian limestone through oölitic limestone, arenaceous and very fine grained, white limestone to calcareous and also nearly pure white sandstone. With these strata occur numerous beds of chert and siliceous oölite, some iron ore and cherty sandstone, the latter due to secondary infiltration of silica and iron. Many of the limestone beds show numerous cavities which have been formed by solution and these are often partly filled with quartz or calcite, indicating extensive transportation of mineral matter.

The mixture of sand and limestone has produced conditions favorable for a great amount of water circulation and chemical activity and the ready disintegration of this series of rocks, with the result that vast quantities of loose sand, and fragments of chert and sandstone have been left on the surface, destroying the agricultural possibilities where the series is exposed and producing the area locally known as the "Barrens."

CONCRETIONARY STRUCTURES

There are a variety of concretions occurring in the region under discussion. In the Utica shale there are many limonite concretions consisting very largely of argillaceous material but often containing

much lime. They are usually in the form of flattened ovals and have been developed since the formation of the shale.

Throughout the Ordovician limestone but especially in the lower and dolomitic beds of the system there are great numbers of chert and flint concretions. In some cases these bodies possess the forms of sponges, and although they have been so much altered that they cannot be definitely identified as sponges, they are believed to be remnants of these animals and it is believed that sponges originally supplied some of the chert around which most of these concretions were built up. Some of these bodies of chert possess a distinctly concentric arrangement, while others are very irregular and often very large. In a few cases these masses of quartz and chert are as much as three feet in diameter and appear to have been cavity fillings in the limestone. The silica varies in composition from flint and chert to rock crystal and in some cases gradations from chert to the phanerocrystalline variety in massive form may be observed in the same body.

Of considerable economic importance are the beds of limonite in the transition series. This mineral forms concretions in the decomposed limestone beds where the limestone has been replaced and fills cracks in a brecciated sandstone which is interbedded with the limestone. These concretions are sometimes a couple of feet in diameter, and are frequently hollow with the central cavity filled with water. When they are broken an explosive sound is produced, showing that they exist under a state of tensional stress. The formation of these bodies probably began by the deposition of iron oxide around the walls of a cavity filled with water and they grew by replacement of limestone.

The source of the iron is believed to be found in the pyrite in the shales and limestones of the Ordovician, in the red sandstones of the Silurian, and probably in the limonitic and sideritic shales and sandstones of the Carboniferous, which have been removed by erosion, leaving their iron contents to be carried downward by meteoric waters. The rapid solution of the interbanded calcareous sandstone and limestone strata permitted a slumping of the solid sandstone, thus producing an extensive sandstone breccia to be cemented with iron oxide.

The most interesting concretions in this area are, however, the calcareous and siliceous oölites.

CALCAREOUS AND SILICEOUS OÖLITES

Calcareous oölites are of such common occurrence that they require but a brief description here. Several beds of them occur

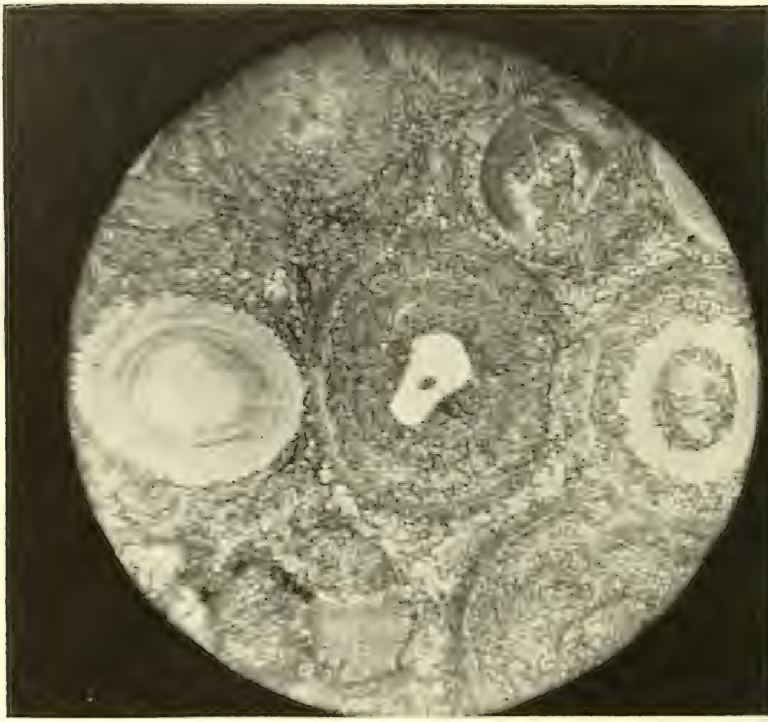

FIG. 2.—Photomicrograph of a calcareous oölite with sand grain as nucleus. ×45

in the transition series in the vicinity of State College and in limestone which has been largely recrystallized. They vary in size from 1.35 mm., the largest measured, to 0.22 mm. in diameter. They have not been seen in the very fine-grained limestone of the series. Their presence in thin sections is often indicated by a single outer circle but at other times the concretion consists of several concentric spheres. There is generally a nucleus of some sort in

the center of the concretion. This is frequently a sand grain and grains have been found varying from 0.6 mm. to 0.04 mm. in diameter and it is believed that some small body has in all cases served as a nucleus. In a few cases what appear to be recrystallized fragments of limestone serve as a central body.

The occurrence of these concretions is believed to be due to the intermixture of sand grains and calcium carbonate. The fact that limestone-conglomerate beds are associated with these rocks suggests that the sea was near the critical level in this area, and portions of limestone, probably not thoroughly consolidated, were from time to time exposed to erosion by fresh water or broken up by shore waves, resulting in the supersaturation of the sea water with calcium carbonate and the deposition of oölitic limstone near the shore. Beds of well-rounded sand grains underlying the oölite beds suggest further a sea advancing upon deposits of wind-blown sand mixed with a certain amount of limestone.

Although siliceous oölite has been reported as occurring in Missouri and Tennessee, it is not a common type of rock in this country. The area in Pennsylvania has therefore been a notable one, although never thoroughly described. Dr. G. R. Wieland wrote a brief description of the rock and as a result it has locally been known as Wielandite and sold by some mineral dealers under that name.[1]

The area in which it occurs in large quantity covers about forty square miles and it is scattered sparingly over a much larger area. It has been reported from the Chambersburg, Pa., area about seventy-five miles south of State College and in rocks of similar age and physical character.[2] The rock occurs in large quantities as broken fragments on the surface and in the form of larger concretionary masses of chert. There are as many as six beds of the rock lying one above the other in the limestone, from five to twenty feet apart. The beds are generally thin, varying from an inch to twenty inches in thickness, and often extremely irregular. The oölites are often nearly white in a dark matrix and almost black in a light-colored matrix. They consist of chert or flint and when

[1] *Am. Jour. Sci.*, 4th ser., IV (1897), 262.

[2] *U.S.G.S., Folio 170.*

polished some specimens make attractive ornaments. The solid oölite rock may grade over into chert with few oölites, and further, to solid chert. The oölites frequently occur in concretions of chert, thus showing a mass of small concretions forming a larger one.

A complete sand grain often forms the nucleus of these concretions but frequently the sand grain is partially or wholly granu-

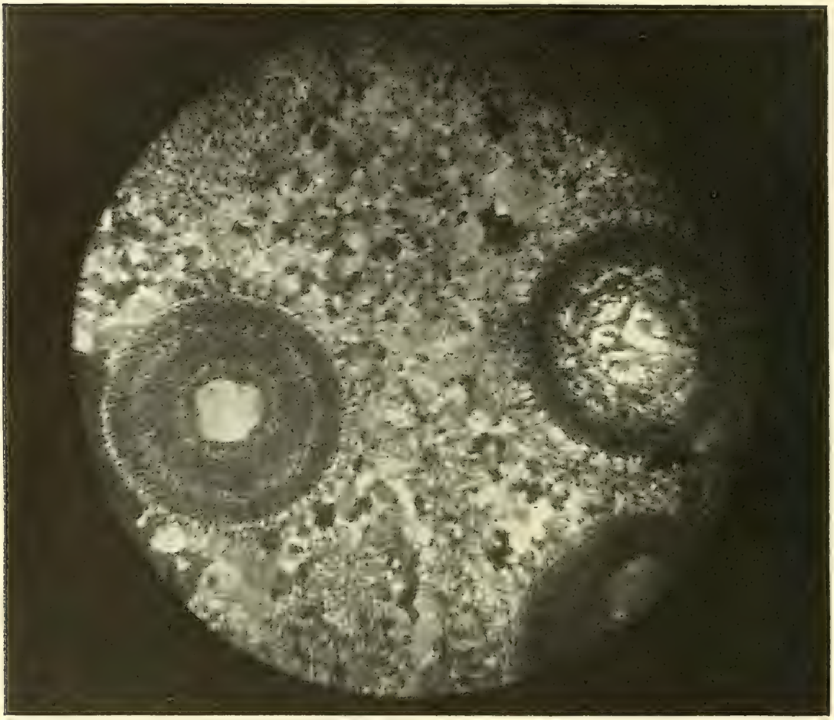

FIG. 3.—Photomicrograph of a siliceous oölite with a sand grain as nucleus. ×35

lated just as quartz grains are in highly metamorphosed rocks, and it is difficult to explain how these could be broken by compression without deforming the concretion, which often remains perfectly round, unless a recrystallization of the oölite as a whole has occurred. In the ability of concretions to reform and recrystallize under metamorphic conditions, as well as in the marked similarity which concretions of any mineral possess in widely separated regions they show a striking similarity to crystals. While so far as

our knowledge of these bodies goes there is not so intimate a relation between the external form and the molecular structure as there is in crystals, there must be some relation on a larger scale, though less perfect, and it is probable that when concretions are more fully understood it will be found that their structures, like those of crystals, are all developed according to definite laws.

FIG. 4.—Photomicrograph of siliceous oölites imbedded in a chert ground mass. ×45

ORIGIN OF THE SILICEOUS OÖLITES

Two theories have been suggested for the origin of the siliceous oölites. In his article on "Eopaleozoic Hot Springs and the Origin of the Pennsylvania Siliceous Oölite,"[1] Dr. Wieland endeavors to show that they originated in the siliceous waters of hot springs. His statements, however, indicate a very limited knowledge of the rock, since he states that it occurs over an area of one square mile

[1] *Am. Jour. Sci.*, 4th ser., IV (1897), 262.

and has not been observed in place. I do not think there is much to justify his theory, as there is no evidence of igneous activity anywhere in the vicinity nor other geological features to suggest the presence of hot springs.

The other theory, and the only reasonable one to my mind, is that they originated by the replacement of limestone. This

FIG. 5.—Photomicrograph of calcareous oölites in various stages of alteration to siliceous oölites. ×45.

explanation was suggested by Barbour and Torrey who made some microscopical examinations and chemical analyses of these rocks without seeing them in the field.[1] The following analyses were made by these men and show a variation in composition from

[1] "Notes on the Microscopical Structure of Oölites with Analyses," *Am. Jour. Sci.*, 3d ser., XL (1890), 246–49.

silica 3.70 to 95.83 per cent and calcium carbonate from 88.71 to 3.45 per cent—thus a gradation from calcareous to siliceous oölite.

	I	II	III	A Single Oölite
	Per cent	Per cent	Per cent	Per cent
SiO_2	3.70	56.50	95.83	SiO_2 99.99
$Fe_2O_3+Al_2O_3$	1.42	1.50	2.93	FeO 00.01
$CaCO_3$	88.71	16.84	CaO 1.93	
$MgCO_3$	8.09	2.60	MgO trace	
Water	.....	12.54	.....	

This alteration is well illustrated in Fig. 5 which shows various stages in the process of replacement. In most cases the replacement begins around the sand grain in the center, if one be present, due probably to the chemical influence of the silica already present in the oölite; but if there be no sand grain as a nucleus this process is more likely to begin in one of the outer rings of the concretion. A number of slides having been examined in conjunction with field observations, there remains no doubt that these siliceous oölites originated by replacement of the calcareous forms.

THE SOURCE OF THE SILICA

The source of the silica is to be found in the cherty remains of sponges and other animals and in the sandstones. According to Van Hise, the organic silica is more readily dissolved than the mineral silica and it is true that in this region the cryptocrystalline variety of the mineral has been much more largely transported than the phanerocrystalline. There are good examples of the solution of chert in a brecciated chert bed in which the fragments have been rounded off and silica deposited along the fractures as cement. In the sandstones there are numerous examples of the partial solution of sand grains and the movement of the silica along cracks in the rocks. This feature is well illustrated by Figs. 6 and 7, where sand grains may be

seen which are partially dissolved and the material redeposited in a granular condition.

It is more difficult to account for the agent which dissolved the silica in this area. Hot water would be an active agent if present, and although the heat developed during the mountain-building period must have been considerable there are no metamorphic

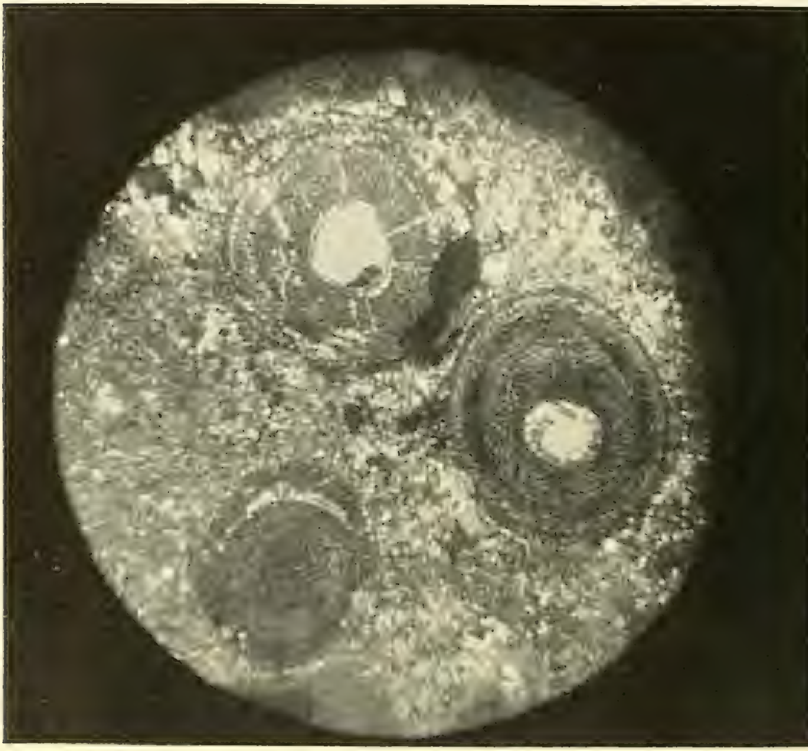

FIG. 6.—Photomicrograph illustrating solution and transfer of silica. ×45

changes of sufficient importance to justify the conclusion that the heat became great enough to effect the solvent action of the meteoric water to any appreciable extent. The presence of carbonic acid doubtless played a part but the extent of this action is uncertain. Alkali waters may have produced important effects but we have no proof that they were present in large amounts and we must therefore turn to organic acids as a recognized agent of importance

and one which has doubtless been very active in this area since it emerged from the sea. In the bulletin, *The Data of Geochemistry*, F. W. Clarke has presented evidence of the great influence of organic acids in the solution of silica.[1] A. A. Julien, T. Sterry Hunt, and many others have made important observations and experiments on the solvent action of these acids, and since there is reason to

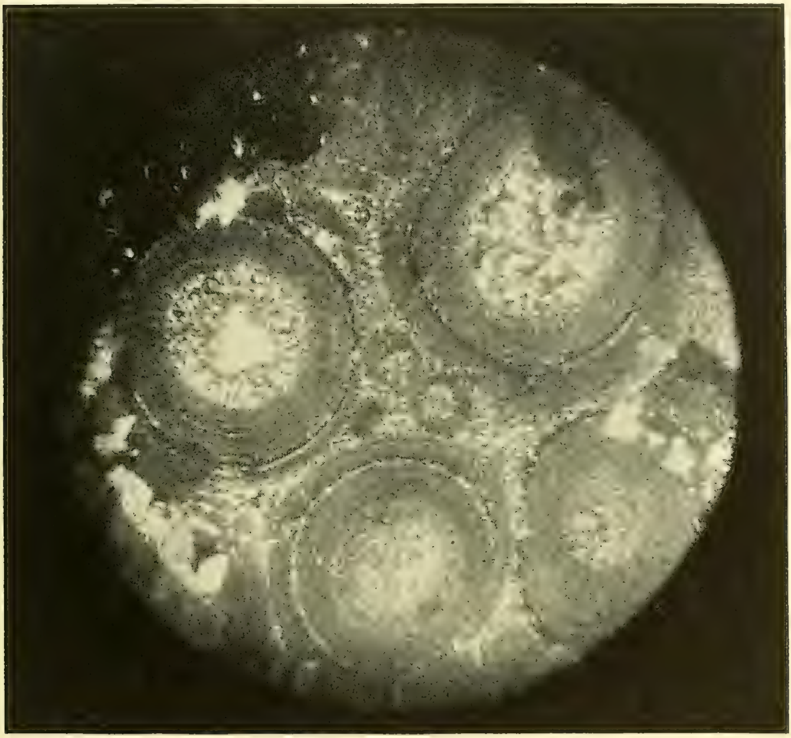

FIG. 7.—Photomicrograph of oölites, illustrating the solution and granulation of the sand grains forming the nucleus of the concretions. × 45.

believe that these agents have been at work for extended periods of time and the solution and transportation of iron and silica are known to be going on at the present time under their influence, it seems reasonable to conclude that organic acids may be regarded as the most important agent in the formation of these siliceous oölites.

[1] *Data of Geochemistry, Bulletin 330, U.S.G.S.*, p. 84.

Petrological Abstracts and Reviews

Edited by ALBERT JOHANNSEN

Campbell, Robert. "Preliminary Note on the Geology of Southeast Kincardineshire," *Geol. Mag.*, VIII (1911), 63–69.

In this paper the author presents the salient points of his rather important studies in this very interesting region. Extending about 3,500 feet southeast from Garron Point is a series of crushed green igneous rocks with intercalated black shales, jaspers, and cherts; and in the shales a remarkable suite of fossils has been found, tending to show that these rocks are of Upper Cambrian age. This series is bounded on the north by an overthrust fault, probably a continuation of the great Highland fault. Resting unconformably upon them to the southeast are 3,860 feet of Upper Silurian (Downtonian) rocks, chiefly sandstones and shales, with volcanic conglomerates and tuffs, and with a basement breccia 200 feet thick. The latter is largely composed of fragments of the underlying Upper Cambian rocks. In one of the sandstone and shale members of this series eurypterids and plant remains were found, and from one stratum an excellent collection of fishes was made. Overlying this series conformably, is the Lower Old Red Sandstone, and above this the Upper Old Red, while still later quartz dolerite dikes are frequently found.

It will be noted from the foregoing brief summary that aside from the detailed mapping several important reversals of the current classification have been made. It has always hitherto been thought that the great Highland fault formed the boundary between the Upper Cambrian and the overlying series and that the basement breccia of the latter was a fault breccia. Again, the 3,860 feet of the Upper Silurian had been previously considered part of the Lower Old Red Sandstone. Finally, the abundance of volcanic material in both of these formations indicates that volcanoes must have been active in this region in pre-Downtonian times, although Geikie had placed the initial outburst at a considerably later date.

G. S. Rogers

Day, A. L., and Sosman, R. B. "The Melting Points of Minerals in the Light of Recent Investigations on the Gas Thermometer," *Amer. Jour. Sci.*, XXXI (1911), 341–49.

The determination of a new thermometer scale (described in a previous article) was based on investigations on the gas thermometer, which resulted in the attainment of a greater accuracy between 400° and 1,150°, and the extension of these temperatures by the extrapolated curve to 1,550° with an absolute accuracy of 2° at that temperature. Upon the more accurate data thus afforded the melting and inversion points of a number of minerals have been reinterpreted, and are here given. The tables are prefaced by certain definitions: thus, melting-point is defined as the point at which a mineral changes from a crystalline to an amorphous (liquid) state; inversion point as that at which it passes from one crystalline state to another; and the difference between the melting interval of slow melting pure compounds, such as quartz, and of mixtures of solid solutions, such as plagioclase, is discussed.

G. S. Rogers

Dewey, Henry, and Flett, John Smith. "On Some British Pillow-Lavas and the Rocks Associated with Them," *Geol. Mag.*, VIII (May, 1911), 202–9; (June, 1911), 241–48.

The basic submarine lava flows form an important series among the Paleozoic igneous rocks of Great Britain, appearing in the pre-Cambrian and in all the Paleozoic systems except the Upper Silurian and the Permian. In most cases they show more or less of a pillow structure, are as a rule very much decomposed, and are characterized by feldspars rich in soda. The name spilite is generally applied. Under this name is described a rock of variable texture, of which the chief components are a soda-rich feldspar, pale brown augite, in some cases remains of olivine, and a fair amount of glassy base which is now wholly devitrified. The feldspar, especially in the more decomposed specimens, is albite and appears peculiarly fresh. From this, and other evidence, the authors argue that much of the albite is secondary and that it probably belongs to a pneumatolytic phase immediately following the extrusion. Associated with the spilites are intrusive rocks of a great variety of types—picrite, diabase, minervite, quartz diabase, heratophyre, quartz keratophyte, soda felsite, and albite granite—ranging from ultrabasic to acid in composition.

Accepting as established the division of the eruptive rocks into two

great suites, the Atlantic and the Pacific, the authors would add to these another, the spilitic suite. This association of rocks is characteristic of regions which have undergone long-continued and gentle subsidence with no important folding. They belong to a natural family that can be clearly distinguished from the Atlantic and Pacific suites.

The constant association of adinoles (albitized shales) with the albitized igneous rocks furnishes a strong confirmation of the theory that there was a great addition of soda after the consolidation of the igneous rocks through the agency of magmatic waters.

E. R. Lloyd

Johnston, J., and Adams, L. H. "Influence of Pressure on the Melting-Points of Certain Metals," *Amer. Jour. Sci.*, XXXI (1911), 501–17.

The paper describes at considerable length a highly efficient apparatus for measuring melting-points with an accuracy of five atmospheres and of .02°. Pressures up to 2,000 atmospheres may be produced, and are transmitted by a high-boiling paraffin oil, the use of this agent enjoining a temperature of 400° as a maximum. The change of pressure of the melting-points of the only four metals melting below 400°, viz., tin, bismuth, lead, and cadmium are given; it was found to be a linear function of the pressure. The latent heat and volume change on melting of these four metals is also computed.

G. S. Rogers

Kraus, Edward H. "A New Jolly Balance," *Amer. Jour. Sci.*, XXXI (1911), 561–63.

The new features of this balance reduce the number of readings necessary for the determination of specific gravity and record the elongation of the spiral spring so that verification of the readings is possible.

Harold E. Culver

Milch, L. "Die heutigen Ansichten über Wesen und Enstehung der kristallinen Schiefer." *Geologische Rundschau*, Band I, Hefte 3 u. 4, pp. 36–58.

L. Milch aims at an impartial presentation of the views of various investigators on the nature and origin of the crystalline schists, with a bibliography of the most important papers.

He points out that two of the fundamental problems of the origin

of crystalline schists are now settled, viz., the source of the crystalline schists, and their relation to time. They have developed from both sedimentary and igneous rocks in various periods, and are not the result of conditions peculiar to the Archean, as formerly supposed. Opinions are still divided, however, on the processes of schist development. These diverse views can be grouped under two heads: (I) those which ascribe the origin of schists to processes independent of the agency of igneous rocks; (II) those which regard the agency of igneous rocks as controlling.

I. The origin of crystalline schists without the agency of igneous rocks.

a) High temperature of the earth's interior.—Hutton and Lyell emphasized the alteration of normal sediments into schists through fusion and recrystallization effected by the high temperature of the earth's interior. This view and the experiments of Daubrie on the alteration of minerals by superheated water, formed the basis of Gümbel's diagenesis (1868), the alteration of mechanical sediments into crystalline schists by superheated waters.

b) Hydrochemical metamorphism.—Bischof and others interpreted the gradation between clay, slate, mica schist, and gneisses as resulting from the chemical action of percolating waters.

c) Dynamic metamorphism.—The fact that schists appear in areas of folded younger rocks led Lossen (1867) to assume that schists are sediments which have been recrystallized through moisture and pressure. Later Rosenbusch (1889, 1891) asserted that the crystalline schists include both igneous and sedimentary rocks which have been altered by geodynamic processes. In 1892 F. Becke concluded that there are two types of dynamic metamorphism. One of deeper zones is effected by recrystallization and resembles contact metamorphism by granites; that of shallow depths involves granulation and is like propylitization in its chemical effect.

In 1894 L. Milch argued that recrystallization could not be effected by pressure alone but must be traced to water heated or superheated by pressure, and that therefore pressure from load would have the same effect as pressure from crustal shortening, and thus differentiated. *Belastungs* and *Dislokations*—metamorphism. L. Milch, (1899), T. J. Sederholm (1891), and Lepsius concluded, independently, that rocks are chemically altered by pressure and percolating solutions combined.

Pressure produces secondary parallel structure (schistosity) by granulation of the original particles, by rotation of platy or columnar particles, so that their major dimensions lie in a plane normal to the

pressure, and by recrystallization. According to A. Heim, rocks which are subjected to pressures far in excess of their strength are in a condition of latent plasticity (1878). In great depths, where stresses are transmitted equally in all directions, rock particles are under hydrostatic pressure, and therefore are deformed without fracture. Where deformation takes place without fracture, shearing on gliding planes as shown by O. Mügge and the increase in plasticity of crystals with rise of temperature as shown by L. Milch on halite are very important.

R. Brauns pointed out in 1896 that, wherever pressure, heat, and hot water act on a rock, alterations in the rock take place until equilibrium is reached.

In 1898 Van Hise divided the earth into a zone of fracture and a zone of flow. The crystalline schists develop in the latter, recrystallization and mineral parallelism being effected by water which causes the transfer of material by solution and deposition from areas of maximum pressure toward areas of minimum pressure. Van Hise also divided the earth's crust into two physical chemical zones, the upper characterized by reactions which liberate heat and the lower by reactions which absorb heat.

L. Milch and others believe that the "law of volume," according to which those minerals which occupy minimum volume tend to develop, is counteracted by high temperature, which tends to bring about the opposite result. L. Milch therefore separates the crust into two zones, an upper in which the "volume law" controls, characterized by the development of hydrous minerals, and a lower zone in which temperature is the controlling factor and practically prevents the development of hydrous minerals. U. Grubenmann designates the transition between these two regions a third zone. The type minerals of the lower zone are pyroxene, garnet, biotite, lime plagioclase, potash feldspar, sillimanite, cordierite, olivine; those of the upper zone, zoisite, epidote, muscovite, albite, and chloritoid. Hornblende, quartz, tourmaline, staurolite, titanite, and rutile are common to both. Milch also believes that the "Kristalloblastic" texture of schists is determined by the crystallizing force of the contemporaneous minerals. Accordingly those minerals assume crystal form which have the densest aggregation of molecules, and preferably those crystal surfaces develop which have the closest spacing of molecules, particularly cleavage faces. Mineral parallelism is less due to mechanical plasticity than to solution and deposition according to the principle of Riecke. The following tables of U. Grubenmann show the relation of the three zones to the rocks which are characteristic of each.

CONTROLLING FACTORS OF EACH ZONE

	Temperature	Heat Toning	Hydrostatic Pressure	Stress	Predominant Effect of Pressure
Upper zone..	Moderate	—	Slight	Great	Mechanical
Middle zone.	Greater	— (—)	Greater	Very great	Chemical (Vol. law, Riecke prin.)
Deep zone...	Very great	—	Very great	Less	Chemical (show recrystallization with retention of form)

TABLE OF ROCKS OF EACH ZONE

Upper zone. Quartz phyllite, sericite phyllite, lime phyllite, chloritoid schist, chlorite schist, talc schist, serpentine, epidote fels, and *topfstein.*

Middle zone. Muscovite schist, muscovite-biotite schist, biotite schist, garnet-staurolite-actinolite schist, nephrite-glaucophane schist, mica gneiss, hornblende gneiss, garnet gneiss, epidote gneiss, marble, quartzite.

Deep zone. Biotite gneiss, pyroxene gneiss, stillimanite-cordierite-garnet gneiss, granulite, garnet-mica schist, garnet fels, eclogite, jadeite, augite fels, marble, quartzite.

II. The various conceptions which assign the origin of crystalline schists to the agency of eruptive rocks can be grouped as:

1. Those which regard gneisses as primary unaltered eruptive rocks.

2. Those which ascribe the crystalline schists to the result of the metamorphic action of igneous rocks on sediments.

Crystallization of magmas under differential pressure or piezo-crystallization (Weinschenk) and the deformation of igneous rocks while still charged with hot juvenile waters (Becke) have been suggested as processes which might explain the first.

Direct contact metamorphism, injections of the intrusive, mainly along parallel zones into the intruded rock, the action of mineralizers, and the absorption of the intruded by the intrusive rocks have been advanced by various writers as processes by which gneisses and schists have developed through the agency of igneous rocks. Michel Levy has pointed out that the alteration of sediments into schists and gneisses adjacent to contacts is not confined to recrystallization, but that there is a zone of impregnation which becomes regional with depth. Slow recrystallization has little effect on texture as contrasted with forcible injection of the intrusive and partial absorption of the older rock.

Occasionally, the contact between a slate and granite is marked by series of parallel injections of the granite into the slate, while masses

of the slate have been submerged in the granite, and partially absorbed, giving rise to *schlieren*. Transferring this observation to large areas of schists, a part of them have been designated as "gneisses of injection" and still another as mixed rocks. Injection of materials is also connected with direct contact metamorphism, often resulting in recrystallization under pressure—piezo-crystallization. Weinschenk designates those schists whose development was conditioned by piezo-contact metamorphism as "alpine facies," and as normal facies those schists which have been developed through impregnation, injection, and resorption without the agency of pressure.

The conception that the action of mineralizers on sediments contributes to the origin of schists has been extended by Termier (1901, 1903) to explain the origin of lenses of peridotite, gabbro, or amphibolite concordantly imbedded in sediments. He regards them as materials which have risen from the deeps along bedding planes, somewhat like a large oil globule, and have locally converted the sediments into *roches vertes*.

Lepsius and Gürich have attached themselves to the French views more fully than other Germans. Lepsius with Barrois emphasizes the absorption of contacts by rising granite magmas; while Gürich has emphasized the action of mineralizers rising from magmas. Lepsius (1903) has maintained that the injection of a granite laccolite concordant with the parallel structures of the intruded rocks results in the intrusive forming granite gneiss, while with discordant injection it forms a massive granite. In both cases large quantities of the intruded rocks are absorbed, giving rise to variations in the composition of the intrusive. Gürich (1904), on the other hand, maintains that the material alteration of sediments and their conversion into gneisses is not due to a granite magma rising from the deeps, but is accomplished by the melting of compressed solid granites enveloped by sediments, on sudden release of pressure which results in absorption of the inclosing schists and alteration to gneiss.

Haug conceives that in geosynclinals, heat, pressure, and ascending mineralizers are sufficient to melt or partially convert sediments into granite magmas which consolidate into magmas on cooling. LeClere (1906) and P. Termier (1907), having similar views, hold that from the upper portions of the masses converted into granite magmas very little injection and impregnation of the surrounding rock results. The action of mineralizers in the upper portions has been just sufficient to convert the rocks into a granite magma.

E. Steidtmann

PATTON, H. B. "Topaz Bearing Rhyolite of the Thomas Range, Utah," *Bull. Geol. Soc. America*, XIX (1908), 177–92.

Discusses the environment and conditions of origin of these rather well-known topazes.

The topaz-bearing rock is a lithoidal rhyolite several hundred feet thick, the last of a series of five flows. Flow structure appears but locally and although the rock shows no solid spherulites, well-developed lithophysae are relatively abundant. These are lined with crystals of quartz, sanidine, garnet, specular hematite, topaz, and bixbyite. Topaz is also an important ingredient of the rock mass and the author describes the three varieties found.

1. Transparent topaz, which always occurs in small cavities in the rhyolite and was formed after the lithophysae were complete.

2. Rough opaque topaz, which abounds in the solid rock as well as in the cavities. The crystals are longer than the transparent variety, gray in color, with ends roughened as though subjected to the action of a solvent. The interior of these crystals is crowded with sharply defined quartz grains.

Forms transitional between groups 1 and 2 are found, from which it would appear that the two varieties are due simply to different conditions of growth.

3. Smooth opaque topaz, which is analogous to the rough opaque variety in habit, color, and occurrence. This variety has been found in but two places in this region, in each case having been developed in a fragment of rhyolite tuff which had been caught up in the rhyolite streams. These crystals are characterized by extreme smoothness of faces and the usually perfect terminations at either end.

The inclosing rock is quite similar in composition to the rhyolite in which it is imbedded. Thin sections show an aggregate of very irregular grains of quartz and of sanidine that vary in size from 0.1 mm. downward. The topaz crystals are perfectly normal and inclose countless minute and invariably sharply defined crystals of quartz which together make up about one-fourth the bulk. No other inclosures are found.

The writer concludes from his study of these topazes: (1) that the period of quartz crystallization was nearly the same as that of the topaz formation, and (2) that the agencies which caused the development of the topaz in the cavities also caused its development in the rock mass, in which space was provided partially by the complete removal of the feldspar and the recrystallization of the silica in definite crystals of quartz. This makes the opaque topazes not exactly foreign matter but an integral part of the rock.

HAROLD E. CULVER

ROGERS, AUSTIN F. "A New Specific Gravity Balance," *Science*, XXXIV (1911), 58–60.

This is a modification of the ordinary beam balance by which the specific gravity is read off directly from the beam. The graduations on the beam are the results of calculations for the various densities. The graduation is in units from 2 to 10, in tenths from 2 to 4, in fifths from 5 to 6, and in halves from 6 to 10. For such minerals as quartz, using a mass of two or three grams, the balance is accurate to about two units in the second decimal place.

HAROLD E. CULVER

ROGERS, G. S. "The Geology of the Cortlandt Series and Its Emery Deposits," *Annals, N.Y. Acad. Sci.*, XXI (1911), 11–86.

The Cortlandt series, best known perhaps through the classic researches of George H. Williams, covers about thirty square miles just southeast of Peekskill, N.Y., on the Hudson River. The following rocks, the distribution of which is shown on a colored map, constitute the principal types, although many of them grade into one another; granite, syenite, sodalite syenite, diorite, gabbro, hornblendite, biotite norite, augite norite, biotite augite norite, hornblende norite, biotite hornblende norite, olivine norite, quartz norite, pyroxenite, hornblende pyroxenite, olivine pyroxenite, biotite peridotite, and many dike rocks. Complete petrographic descriptions are given, together with seventeen new analyses. Surrounding the series is the Manhattan schist, associated with the Fordham gneiss and Inwood limestone, and xenoliths of these rocks are found in the series itself. The latter is therefore younger, but is older than the Triassic shales across the river, and is probably late Paleozoic. In general, no metamorphism is found in the series, but an original gneissoid structure is common; and from the evidence afforded therein, as well as from the distribution of the types, it is thought that the pyroxenite group was extruded first, followed closely by the norites, with the granites distinctly later. The position of the diorite group is problematical; it is possible that these types are the product of reactions between the igneous rocks and the surrounding metamorphics.

It is found that contact action between the igneous rocks and the limestone give rise to abnormal wernerite, tremolite, and grossularite mixtures; and similarly, contact with the aluminous schist produces a concentration of the biotite and magnetite of the latter, with the frequent formation of almandite, sillimanite, spinel, corundum, etc. The

similarity of the phenomena exhibited at the emery mines with those shown on the borders is thought to indicate that the ore owes its origin to the inclusion and assimilation of schistose xenoliths, producing a local supersaturation of alumina which resulted in the deposition of corundum.

AUTHOR'S ABSTRACT

SCHWARTZ, E. H. L. "What Is a Metamorphic Rock?" *Geol. Mag.*, VIII (1911), 356–61.

In propounding this apparently academic query, the writer is actuated by the appearance of certain taxonomic inconsistencies in the latest treatise on metamorphism—Grubenmann's *Die kristallinen Schiefer*—which he believes would have been obviated by a more precise definition of the term. Van Hise defines a metamorphic rock as one that has been altered; but it is tacitly understood that a sediment does become metamorphic through induration, for example, nor will the development of pegmatitic structure remove a granite from the igneous class. Starting with the conception of the three zones of metamorphism, marked by increasing pressure and by the increasing molecular volumes of the rocks formed, Professor Schwartz notes the fact that the molecular volume of a true igneous rock will be still higher. Now solvent water is the agent active in forming the characteristic minerals and structures of igneous rocks, and this leads to an essential difference between them and the metamorphics. In the former the pressure is so great that the solid particles move freely into the solvent, allowing the chemical affinities of the molecules to satisfy themselves, while in the latter only the borders of the grains are rendered fluid, the chemical affinities are restricted, and the law of least molecular volume comes into play. Thus a metamorphic rock would be one in which the internal or molecular pressure had been less than the external or dynamic, so that certain peculiar minerals have resulted. Some of these, such as epidote, lose their crystalline form long before fusion, indicating a probable expansion of the molecule, under conditions which allow the chemical affinities full play. These minerals when found in a rock may therefore be accepted as criteria of its real nature.

This paper does not arrive at any very satisfactory conclusion, from a practical standpoint; but it must be remembered that it is primarily a protest against the want of definitiveness in the terms ordinarily employed, and that the author's recourse to physical chemistry is both tentative and reluctant.

G. S. ROGERS

WORKMAN, RACHEL. "Calcite as a Primary Constituent of Igneous Rocks," *Geol. Mag.*, VIII (May, 1911), 193–200. Pls. 2.

In this short paper is presented a very interesting description of the alkali igneous complex on the islands of Alnö and Langörsholmen, Sweden. The evidence seems conclusive that in this group of rocks calcite occurs as a primary constituent; in fact the two chief types of igneous rock are nephelite syenite and an almost pure calcite rock. Between these two extremes there are all gradations. No definite order of crystallization can be observed but the calcite is as a rule the last mineral to crystallize. The same minerals occur in the two types of rock except that cancrinite, which is abundant in the nephelite syenite, is absent where calcite is abundant.

The author calls attention to other areas of igneous rocks where calcite has been described as a primary constituent and discusses briefly the possible magmatic history of the mineral. Daly's theory of the absorption of limestone by a subalkali magma does not seem to be applicable here for lack of the necessary limestone. Högbom's conclusion is, that the calcite has crystallized from the magma in a manner exactly analogous to the other minerals.

E. R. LLOYD

REVIEWS

The Geology of the Neighbourhood of Edinburgh. 2d ed. By B. N. PEACH, C. T. CLOUGH, L. W. HINXMAN, J. S. GRANT WILSON, C. B. CRAMPTON, H. B. MAUFE, and E. B. BAILEY, with contributions by J. HORNE, W. GIBSON, E. M. ANDERSON, and G. W. GRABHAM, and petrographical chapters by J. S. FLETT, Memoirs of the Geological Survey, Scotland. Tanfield, 1910. Pp. 445; figs. 19; maps 1.

Since the publication of the first edition by H. H. Howell and Sir Archibald Geikie in 1861, more detailed study has brought about newer interpretations, and the development of mining has allowed more discoveries to be made. The present edition brings up to date the interpretation of the geology of this district.

The rocks of the region represent periods of sedimentation, extrusion, and intrusion from the Silurian to the Permo-Carboniferous, from which time on there is a hiatus until the Pleistocene and Recent which are represented by glacial, lake, and other characteristic deposits. The sedimentary formations and the igneous rocks are described in great detail, and the paleontology and petrography are very complete. One chapter is given to the economic geology, which is limited principally to the coal deposits.

A complete bibliography covering the geology of the area described, is appended. The geologic map of the entire region reported on does not accompany the memoir. A. E. F.

The Stratigraphy of the Older Pennsylvanian Rocks of Northeastern Oklahoma. By D. W. OHERN. Research Bull. No. 4, State Univ. Okla., 1910. Pp. 40; table 1; map 1.

In this bulletin the Pennsylvania strata are discussed, and a few new subdivisions are differentiated and named. The rocks of southeastern Kansas, studied by the Kansas geologists, are correlated with those of northeastern Oklahoma. A. E. F.

Geology and Water Resources of the San Luis Valley, Colorado. By C. E. SIEBENTHAL. Water-Supply Paper No. 240, U.S. Geol. Survey. Pp. 128; figs. 15; pls. 13.

The geography of the valley is described with special reference to the hydrography. At the point where the Rio Grande leaves the valley,

its volume is always above a certain minimum due to an artesian supply. The formations of the valley are the Santa Fé, composed of conglomerates and intercalated lava flows, and the Alamosa, a lake deposit, which, because of its sand beds interstratified with a series of blue clays, satisfies the necessary conditions for an artesian circulation.

Most of the waters from the streams sink into the alluvial fans soon after they enter the valley, and this furnishes the water supply for the aquifers. If all the waters entering the valley were used for irrigation, it is estimated that 20,000–25,000 acres could be made productive. Most of the 3,234 wells in the valley are flowing, and a large number are used primarily for irrigation. They are described by localities; many records and twenty analyses of the waters are given. A peculiarity of the wells in the trough of the valley is the presence of small amounts of gas and brownish-colored water due, respectively, to vegetable accumulations and alkali deposits in the Alamosa formation, formed during an arid time when the lake was much shrunken. Springs are not uncommon, and of these several are of the thermal type. The accompanying topographic map shows the limits of the flowing wells, the gas field, and the colored waters.

A. E. F.

The Origin of the Thermal Waters in the Yellowstone National Park. By Arnold Hague. *Science, N.S.*, XXXIII, 1911, 553–68.

The conditions of the region are such as could give rise to springs. The gases escaping from the waters and the substances held in solution could be derived from the rocks traversed, and they vary in composition according to the chemical nature of the rocks through which they ascend. For these reasons it seems that these thermal waters have a meteoric origin. Of interest is the clear explanation offered for considering a geyser but one phase in the development of some hot springs.

A. E. F.

Reconnaissance of the Geology and Mineral Resources of Prince William Sound, Alaska. By U. S. Grant and D. F. Higgins. Bull. 443, U.S. Geol. Survey. 1910. Pp. 89; figs. 9; pls. 12.

The two divisions of the sedimentary rocks are the Valdez and the Orca groups, both of which are closely folded, and the latter lies unconformable on the former. Basic flows of greenstone, ellipsoidal in many places, are so intimately interstratified with the Orca, that they are discussed as a part of that group. Granitic bosses and dikes of diabase,

gabbro, diorite, and aplite intrude the sedimentaries. The petrography of the igneous rocks is rather detailed for a reconnaissance report.

Sheared zones occur in the greenstone, and these carry important copper values, the only mineral of importance being chalcopyrite. Practically no oxidized zones are found. Auriferous quartz veins also occur in the region, and one gold mine is in operation. A. E. F.

Geology and Mineral Resources of the Solomon and Casadepaga Quadrangles, Seward Peninsula, Alaska. By PHILIP S. SMITH. Bull. 433, U.S. Geol. Survey. 1910. Pp. 234; figs. 26, pls. 16.

This bulletin is the first of a series to describe in detail the geology of Seward Peninsula. The results of reconnaissance work for the whole peninsula are discussed, to give a general setting, and then the detailed geology of these two quadrangles is described. The rocks of the region are of sedimentary and igneous origin, practically all of which are highly metamorphosed. The metamorphosed sediments consist of the Solomon schist (pre-Ordovician [?]), the Sowik limestone (Ordovician [?]), the Hurrah slate (post-Ordovician [?]), and the Puckmummie schist (post-Ordovician). The metamorphosed igneous rocks are the Casadepaga schist, and greenstones. After the intense diastrophic movements that affected these rocks, others were deposited and intruded. Of the later sediments, but very small amounts of a conglomerate are left, and the igneous rocks consist of granitic and basic intrusives, none of which cover any considerable area. Unconsolidated deposits of recent age are found as stream gravels, high level gravels, and in the coastal plain.

This region is of economic importance because of its gold production. Auriferous quartz veins are numerous, but their values have been such that only one mine has ever been on a paying basis. The most important veins are largely limited to the Hurrah slate, and the contact of the Sowik limestone and the Solomon schist. By far the largest production has been from placers in the river gravels, and the locations of the ones where the best values are recovered is down stream from the outcrops of the Sowik limestone. A few dredges are in operation, and they have been very profitable. A. E. F.

The Copper Handbook, Vol. X, 1910–11. By HORACE J. STEVENS. Houghton, Mich., 1911.

As in the past, the work contains condensed information regarding all the known copper mines of the world, giving a sketch of the financial

history, and a brief statement of geologic and economic conditions of each. It forms an invaluable book of reference for everyone interested in the copper industry. The data are brought up to July, 1911.

A. D. B.

The Relation of Bornite and Chalcocite in the Copper Ores of the Virgilina District of North Carolina and Virginia. By FRANCIS BAKER LANEY. *Proc. U.S. National Museum,* XL. Washington, 1911. Pp. 523–24; pls. 63–69.

After a brief discussion of the geology of the region the author describes sections of the ores from a microscopic study. None of the bornite appears to be secondary. The chalcocite occurs as secondary veinlets in the bornite, and as intergrowths with bornite showing that in the latter case the two minerals formed simultaneously. The author confirms Graton's view that the chalcocite is primary, and the evidence is convincing. If, however, the ore deposits are older than the metamorphism, the same result could arise from the recrystallization of a secondary ore. This possibility has not been discussed but is suggested by the work of Emmons in Maine and in the Ducktown region.

A. D. B.

Iron Mines and Mining in New Jersey. By W. S. BAYLEY. Geological Survey of New Jersey, Vol. VIII, 1910. Pp. 512; pls. 13; maps 1; figs. 31.

The report gives a brief history of iron mining in New Jersey since its initiation in 1685. A brief outline of the geology of New Jersey pertinent to the subject follows, and the remainder of the report deals with the iron ores themselves. These are of four types, bog ore, limonite, red hematite, and magnetite. In early years considerable bog ore was utilized. Later, the limonites became of importance. At present, the magnetites are mined almost exclusively. The ores are described separately, as to their appearance, chemical composition, manner of occurrence, origin, and production. Much space is given to the description and history of individual mines. H. C. C.

The Mineral Production of Virginia during 1909 and 1910, Biennial Report on. Virginia Geological Survey Bulletin No. 6. Pp.123.

The mineral production for 1909 and 1910 is summarized, and compared with that for several previous years. Iron, coal, and clay are of major importance. The production of most of the substances mined

is nearly stationary or is decreasing, except in the case of coal. About six and one-half million tons of coal were mined in 1910, as against four and three-quarter million tons in 1909. H. C. C.

Annual Report of the Bureau of Mines, Ontario. Vol. XX, Part 1, 1911. Pp. 284; figs. 39; pls. 11; maps 4.

The mineral production of Ontario for 1910 is reviewed, and compared with the productions for the past five years. Most noteworthy is the great increase in the amount of silver mined in the Cobalt district, an increase of over $3,000,000 above that of the previous year. This raises the production from these mines to over $15,000,000 for 1910, and places Canada third in rank among the silver-producing countries of the world. The value of the nickel from the Sudbury mines also reaches over $4,000,000 in 1910, an increase of more than $1,200,000 above the previous year.

The remainder of the report contains the following papers: "Mining Accidents," by E. T. Corkill, pp. 59–85; "Mines of Ontario," by E. T. Corkill, pp. 86–118; "Silver in the Thunder Bay District," by N. L. Bowen, pp. 119–32; "The Sturgeon Lake Gold Field," by E. S. Moore, pp. 133–57; "Gold Fields of Lake of the Woods, Manitou, and Dryden," by A. L. Parsons, pp. 158–98; "Vermilion Lake Pyrite Deposits," by E. S. Moore, pp. 199–213; "Iron and Lignite in the Mattagami Basin," by M. B. Baker, pp. 214–46; "Notes on the Salt Industry of Ontario," by N. L. Bowen, pp. 247–58; "A Geological Trip in Scotland," by W. G. Miller, pp. 259–69; "The Mining Law of Ontario," by S. Price, pp. 270–79; "The Laurentian System," by W. G. Miller and C. W. Knight, pp. 280–84. H. C. C.

Notes on the Geology of the Swedish Magnetites. By D. H. NEWLAND. New York State Museum Bulletin 149, Pp. 107–19.

The author describes the nature, occurrence, and genesis of the principal magnetite deposits of Sweden, viewed while attending the International Geologic Congress at Stockholm in 1910, and compares them as far as possible with similar American deposits. While mentioning the bog-iron deposits and the low-phosphorous magnetites, he takes up in particular detail the great deposits of high-phosphorous magnetites at Kiruna and Gellivare. These ores occur in lenses, bands, and chimneys, as magmatic segregations from quartz porphyries and sodic syenites. The Kiruna ores are massive and non-granular, having been subjected

to little or no metamorphism since deposition. At Gellivare the rocks have been subjected to powerful metamorphic agencies, which have caused the magnetites and their included minerals to assume a coarsely crystalline phase. The writer regards the Adirondack magnetites as illustrations of similar deposits that have undergone a still more extreme metamorphism. H. C. C.

Biennial Report of the State Geologist. North Carolina Geological and Economic Survey, 1911. Pp. 152.

Discusses the work of the Survey during 1909 and 1910 as to highways, hydrography, forestry, magnetic surveys, and fisheries.

H. C. C.

Uranium (Radio-active) Ores and Other Rare Metals and Minerals in South Australia. Geological Survey of South Australia, 1911. Pp. 12; plates 4; map 1.

The report gives an account of recent discoveries of large deposits of low-grade uranium ores in the Flinders range. The ores occur in the oldest rocks of the state; the outcrops consist of a gossan of quartz and iron oxides principally, containing 0.2–0.5 per cent of uranium trioxide. The uranium is present as secondary uranium minerals, torbernite, autunite, gummite, carnotite, etc. It is stated that values are found to increase with depth, and that primary uranium minerals are expected to be found shortly. Other rare earths, as ceria, thoria, yttria, etc., also occur in the deposits. H. C. C.

Comparative Sketch of the Pre-Cambric Geology of Sweden and New York. By James F. Kemp. New York State Museum Bulletin 149, pp. 93–106.

The oldest rocks of the Swedish pre-Cambrian consist of a great complex of both igneous and sedimentary types; the sediments include conglomerates, quartzites, limestones, sedimentary gneisses, etc.; and the igneous, a great variety of intrusives of the highest interest. It is in these rocks that many of the great deposits of iron ore are found. Intrusive into this great complex are the Serarchean granites, which are divided by Högbom into four principal types. Following the intrusion of these granites, and closing the Archean, came a period of vast denudation, considered by Högbom as the greatest time-break in the history of the earth. On the eroded surface the Jatulian sediments

were later deposited; in Finland these consist of quartzites, schists, dolomites, and beds of anthracitic carbon; in age they are probably equivalent to our Upper Huronian. Into these, after a period of folding, the rapakivi granites were intruded; and, at a still later date, a variety of other intrusives. Then came a great period of denudation and very complete peneplanation, before the deposition of the Jotnian sandstones. These sandstones are subaerial deposits, little metamorphosed, and considered the equivalent of our Keweenawan. After another period of complete peneplanation the Cambrian was laid down. Unlike most of the Cambrian of America, the Swedish Cambrian has a weathered breccia as its basal facies. H. C. C.

A Geographical Report on the Franz Josef Glacier. By JAMES MACKINTOSH BELL, with Topographical Maps and Data by REGINALD PALMER CREVILLE, and Botanical Notes by LEONARD COCKAYNE. Department of Mines, New Zealand Geological Survey. Wellington, New Zealand, 1910. Pp. 14; maps 3; photographs 6.

The Report is a very readable description of the Franz Josef Glacier system, which is of the valley type, and descends to an altitude of only 692 feet above sea-level, although it lies in latitude below 44°. The topographic maps are not contour maps. The Botanical Notes give a list of the plants found between the glacier and the coast-line.

A. E. F.

A Report on the Geological and Mineral Resources of the Arbuckle Mountains, Oklahoma. By CHESTER ALBERT REEDS, PH.D. Oklahoma Geological Survey. Bulletin No. 3. Norman, Okla., December, 1910. Pp. 69; plates 24; figs. 10.

The Arbuckle Mountains are a moderately dissected plateau ranging in elevation from 1,300 feet in the north and west to 750 feet in the southeast portion. The mountains came into existence in Pennsylvanian times, and since then have been subjected to elevation at three different times, as attested by records of the Cretaceous base level and the interrupted Miocene and Pleistocene erosion cycles.

The region consists of pre-Cambrian granite and porphyry upon which rest unconformably approximately 10,000 feet of Paleozoic sediments, ranging in age from Middle Cambrian to Pennsylvanian, and

which have been differentiated into ten formations, of which only one, the Hunton, has been fully studied.

The structure of the Arbuckle Mountains consists of two sets of complex folds that intersect each other at almost right angles, forming pitching anticlines, synclines, domes, and basins. These have been considerably affected by subsequent erosion and normal faulting.

The economic resources of the Arbuckles have been but little utilized. They consist of iron and manganese, among metallic minerals, and of extensive bodies of asphalt, glass sand, cement materials, building stone, sand, gravel, etc., of the non-metallics. A. E. F.

"Osteology of Pteranodon." By GEORGE F. EATON. *Memoirs of the Connecticut Academy of Arts and Sciences*, II (1910), pp. 1–38; Pls. 31.

The writer, whose acquaintance with vertebrate paleontology began with the collection of a specimen of *Pteranodon*, takes especial pleasure in the expression of his appreciation of the present memoir by Dr. Eaton. The rich material of this genus in the Yale collections is unsurpassed, and it has been well utilized in the present paper, with its large number of excellent illustrations. Nearly every important point in the osteology of these remarkable creatures has now been conclusively determined, and of all nothing is more anomalous than the structure of the palate, which as figured and described by the author (and the writer can testify, correctly) seems inexplicable for a vertebrate. The extraordinary occipital crest justifies Marsh's original figures, though the author finds in other specimens or species a shorter crest as figured by Williston; and it is also another evidence of that peculiar osteological acumen possessed by Marsh which has seldom been excelled among paleontologists. One could wish that Dr. Eaton had entered more fully into some of the disputed points about the relationships and characters of the genus, but the omissions are immaterial in comparison with what he has given.

S. W. W.

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DYNAMIC RELATIONS AND TERMINOLOGY OF STRATIGRAPHIC CONFORMITY AND UNCONFORMITY[1]

W. O. CROSBY
Massachusetts Institute of Technology, Boston

GENERAL DEFINITIONS

Next in dynamic and structural importance to the stratification of sedimentary rocks are the relations of the strata designated by the terms conformity and unconformity. Most briefly defined, and with emphasis laid, as it should be, upon the dynamic aspect of the phenomena, conformity means that the process of deposition was not, and unconformity that it was, interrupted by erosion.

In other words, conformity implies that deposition was essentially continuous, that no true hiatus and consequently no period of erosion (the antithesis of deposition) intervened during the deposition of the series of which this structure is predicated. This definition, it will be noted, tacitly assumes that deposition does not fail absolutely from mere lack of material, where other conditions are favorable, although over extensive areas, including especially the abyssal depths of the ocean, it may be almost infinitely

[1] In the preparation of this paper the author has had the advantage of discussing the subject with those two accomplished stratigraphers, Dr. A. W. Grabau and Dr. H. W. Shimer; and their helpful criticism and suggestions are gratefully acknowledged.

slow, long periods of geologic time being, for the particular region, virtually, though not absolutely, unrecorded; but such an apparent or even actual gap in a sedimentary series is consistent with perfect conformity, for the one absolute essential of a conformable series is that it be in no part a record of erosion.

Unconformity, on the other hand, implies a true hiatus, an actual interruption of deposition by erosion, followed by further deposition. The erosion may be terrestrial (peneplanation) or littoral (marine planation). But it is necessary to emphasize the importance of the time break in order to exclude from consideration the localized erosion, both terrestrial and marine, due to shifting and variable currents and often closely accompanying deposition in both space and time. This phenomenon, known as contemporaneous erosion and deposition, giving rise locally, in one and the same sedimentary series, to numberless examples of the appearance, but never the reality, of true stratigraphic unconformity, is best relegated, with cross-bedding or current lamination, to the category of the irregularities of stratification. The one is not true unconformity any more than the other is true delta structure. The paramount, the vital or dynamic, interest of unconformity is found in the clear and unquestionable proof which it affords of a double interchange of land and sea, or at least of wide or general areas of erosion and of deposition. An important time break or hiatus is a necessary implication; and thus arises, somewhat incidentally, the great value of unconformity in stratigraphic demarkation and classification.

In order to avoid other possible misconceptions, it is needful, also, that attention be directed particularly to the fact that both conformity and unconformity are absolutely definite structures, definite in the sense that each is always sharply localized stratigraphically and may be predicated of a particular stratigraphic plane or contact. In other words, the student may put his finger on a definite line and say, "Here is conformity" or "Here is unconformity," as the case may be. This point is, perhaps, clearest for unconformity; but it must be obvious, on reflection, that conformity does not require that the top and bottom of a series should be parallel. Conformity exists throughout if at each line of stratifi-

cation the structure is sensibly parallel and the deposition essentially continuous, continuity of deposition alone constituting conformity, and of this continuity parallel lamination is a common but by no means a necessary or infallible sign.

Again, these mutually exclusive structures are universal in the sense that the strata are everywhere either conformable or unconformable. And since true unconformity is absolutely inconsistent with continuous deposition, no mere irregularity of deposition, no matter how marked, can give rise to an unconformity. In general confirmation of this we have the fact that, so far as clearly recognized, each type of irregularity has, as we have seen, a designation of its own. In a later paragraph, additional names will be proposed for phases of conformity not always sharply distinguished from unconformity.

SEDIMENTARY PROVINCES

A. Continental
- *a*) Terrestrial[1] (continental surface)
  The deposition may be:
  1. Eolian
  2. Fluvial
  3. Lacustrine
  4. Glacial
- *b*) Coastal (continental margin)
  The deposition may be:
  1. Estuarine and deltal
  2. Littoral (shore)
  3. Marine (continental platform)

B. Oceanic (abyssal depths)

An exhaustive scheme is not aimed at here; but the purpose is, rather, to set forth the commanding importance, as a theater of sedimentation, of the coastal zone or province. Erosion is the normal geologic activity of the terrestrial province; and terrestrial

[1] The growing tendency to designate land deposits as terrestrial instead of continental meets the writer's approval. Terrestrial is clearly the more accurately descriptive term, since it does not exclude insular deposits, and does not include the deposits of the continental platform, which are as truly continental as any.

deposits, although in part widespread, are, nevertheless, characteristic of but a small fraction of the land surface, and are likely, except, in general, under graben conditions (localized depressions), to be relatively thin. They are also, in large part, transitory, being ultimately (perhaps during subsidence) reworked and deposited in the coastal province. Also, the oceanic or truly abyssal deposits, although of relatively limitless area, are especially noteworthy for their thinness and their wonderful uniformity over wide expanses.

The coastal zone or province, although the narrowest, is, then, as every student knows, the specially important field of relatively permanent sedimentation. In other words, the old, broad generalization still holds, that sediments are derived from the land and deposited in the sea, and chiefly in the marginal portion of the sea; although the finer part of the terrigenous (non-cosmic) detritus may reach the abyssal or truly oceanic depths. The calcareous and siliceous oozes characteristic of the deep sea are, it may be observed in passing, truly land-derived, although the material is transported in solution and deposited by organic agency.

Again, in the terrestrial province the sediments are during their deposition almost constantly exposed to erosion. Contemporaneous erosion and deposition is peculiarly characteristic of this province, and the frequent occurrence of the resultant pseudo-unconformity tends to make the recognition of true or significant unconformity difficult. In the oceanic province, on the other hand, uniformity and conformity reign supreme and unconformity is virtually wanting. But in the coastal province the migrations of the shore are extremely favorable to the alternation of deposition and erosion over extensive areas and the development of true or normal unconformity.

The grand result of sedimentary activity in the coastal province is the building of the broad bench or terrace fringing the continent, of which the dry, landward portion is known as the coastal plain and the wet, seaward portion as the continental platform; and nowhere, probably, has the coastal province a more normal development than on the Atlantic and Gulf borders of North America.

THE COASTAL PLAIN OF EASTERN NORTH AMERICA[1]

The coastal province includes, as we have seen, the coastal plain and the continental platform. Concerning the geologic history and structure of the former our knowledge is fairly full and accurate and it is becoming more so with every new boring and excavation; while our knowledge of the latter is, and apparently must remain, largely conjectural or, more accurately, inferential, consisting of more or less valid deductions from what is known of the coastal plain. Hence it is natural that attention should now be concentrated upon the latter, although it is much the smaller part of the province. It is, however, the landward part and therefore the part that has been most affected by changes of level and consequent migrations of the shore; and it is for this reason, especially, much the more promising part as a field for the study of unconformity. A brief outline of the geologic history of the coastal plain will serve to bring into view the general relations of the strata which are the main objective of this paper, relations which are believed to hold for coastal plains generally, throughout the world and throughout geologic history.

During Jurassic time, what is now the Atlantic seaboard of the United States was elevated and suffering erosion; and on the complex geologic structure handed down from Paleozoic and older and from Triassic times was developed the so-called Cretaceous peneplain. This peneplained surface of the older formations is the true foundation or bed-rock of coastal plain geology—the floor and primary datum plane of coastal plain stratigraphy.

The subsequent history of the seaboard is comprised in an oscillatory and possibly isostatic seaward tilting of the Cretaceous peneplain, attended landward by erosion, resulting, during periods of relative stability, in the partial development of successively lower base-levels; and attended seaward by more or less continuous deposition and the development of the entire coastal plain

[1] This paper is one of the fruits of a somewhat elaborate study of coastal plain geology made under the auspices of the Board of Water Supply of New York City, with special reference to the geologic relations of the ground-water of Long Island. This investigation will, in due course, be published in full as a bulletin of the New York Geological Survey.

series of Cretaceous and later sediments. This general crustal movement—depression seaward and elevation landward—has continued until the originally nearly level bed-rock surface (the Cretaceous peneplain) now slopes seaward beneath the coastal plain 75 to 100 feet per mile. Upon this sloping peneplain the coastal plain, which is continued seaward in the continental platform, holds the relation of a built terrace—thinning landward and thickening seaward.

The oscillatory character of the movement has determined repeated seaward and landward migrations of the shore, with the result that within what may be called the axial zone of the seaboard or landward margin of the coastal plain, deposition and erosion alternated and stratigraphic conformity has been interrupted by unconformity; while seaward throughout a large part of the coastal plain and the whole of the continental platform, deposition has been relatively uninterrupted and conformable; and landward beyond the limits of the coastal plain, erosion has similarly prevailed.

Obviously these conditions are likely to continue until the distant future time when the increasing burden of unconsolidated sediments, accompanied by a gradual rise of the isogeotherms, has induced softening of the sub-crust or true bed-rock, and plication, with consequent crustal thickening and uplift, ensues. Thus when the revolution is complete and the land is again base-leveled by erosion, the way will have been prepared for another widespread or universal unconformity and the beginning of another grand cycle of deposition, leading to the development of a new continental platform and coastal plain.

UNCONFORMITY IN THE COASTAL PROVINCE

No attempt at a complete enumeration of the unconformities of the coastal plain (the accessible part of the coastal province) above the Cretaceous peneplain—the universal and absolute unconformity which forms its floor—is likely to be successful, except locally, for the simple reason that the crustal oscillations in which the unconformities have their origin have not affected uniformly all parts of the seaboard. The oscillations are known to have

varied greatly longitudinally or in the trend of the coast; and transversely their differential effect must have been most marked because of the normal seaward tilt, increasing downward, of the coastal plain formations. The major divisions of these formations may be correlated with the major oscillations of the crust; and the principal unconformities are, therefore, interformational; while relatively local and subordinate unconformities may be described as intraformational or, better, as marking off, or giving distinctness to, the minor divisions of the geologic record.

The main point demanding attention now, however, is the striking contrast of all these coastal plain unconformities, both inter- and intraformational, to the great unconformity of the Cretaceous peneplain, forming the floor of the entire coastal plain series and recording a hiatus and a stratigraphic break of the first magnitude. This basal unconformity of the coastal plain is characterized by the profound deformation (plication, faulting, etc.) and metamorphism as well as by the extensive erosion of the diverse bed-rock formations before the deposition over them of the coastal plain series began. In other words, this unconformity is the joint product of deformation and erosion, while all the unconformities, both major and minor, actually within the coastal plain series are characterized by erosion alone, and exhibit no sensible deformation of the older before the deposition of the newer formations. In the one case the beds are discordant, and in the other case they are accordant in dip and strike.

TERMINOLOGY OF UNCONFORMITY

Grabau,[1] recognizing the numerous examples of accordant unconformity in the geologic record and the desirability of a distinctive name, has proposed for them the designation *disconformity*, reserving *unconformity* for the discordant type. This use of the prefix *dis-* is clearly unfortunate, since it implies a divergent and not a parallel relation of the strata. It is, moreover, desirable that we should have a generic term, applicable to all cases of a lack of conformity; and for this purpose *unconformity* has the sanction of usage and etymology. Unconformity should not, therefore, be

[1] A. W. Grabau, *Science* (N.S.), XX, 534.

restricted to a particular type of stratigraphic break, even though that one be the most important.

My first thought was to propose for the two types of unconformity—the parallel and divergent—the prefixes *para-* and *dis-*, respectively, thus matching the distinction in physics of paramagnetism and diamagnetism. But the prior use of *dis-* in the contrary sense has seemed to preclude, or at least to render undesirable, its use in this new, though etymologically more correct, sense. I therefore propose, instead, the prefixes *para-* and *clino-*. The terms may be written in full, and with a hyphen to aid pronunciation, thus, para-unconformity and clino-unconformity; or they may be abbreviated to parunconformity and clinunconformity.

Although these terms are, and, for the sake of convenience in designating and describing the phenomena, ought to be, structural, it is important, nevertheless, to recognize that the real, the fundamental, distinction, is dynamic; and of course the student should not be misled by the fact that a clinunconformity may locally show a parallel relation of the strata. The full significance of the distinction for which these terms stand is realized only in the broad view. We then see that parunconformities must be relatively frequent and local, recording the minor vertical oscillations of coastal plains undergoing progressive and, possibly, isostatic settling; while clinunconformities are few and widespread, recording the great crustal revolutions accompanied by profound readjustment and interchange of land and sea.

CONFORMITY IN THE COASTAL PROVINCE

Deposition within the coastal province is limited by two planes diverging seaward: (1) the level surface of the sea, the elevation of which is constantly shifting, with a general tendency to rise relatively to the land; (2) the sloping bed-rock surface, the buried Cretaceous peneplain. It is a significant fact that if the Cretaceous peneplain be projected seaward under the continental platform with its proved gradient beneath the coastal plain, it will be found at the foot of the continental slope approximately continuous with the floor of the abyssal ocean. We cannot doubt, therefore, in view of the shallow soundings of the continental platform, that the sedi-

ments of the coastal province, resting upon the Cretaceous peneplain, thicken enormously seaward. This has been abundantly confirmed by borings for individual members of the coastal plain series. Thus the Miocene formation, hardly a hundred feet thick near the landward edge of the coastal plain in the vicinity of the Delaware River, is more than a thousand feet thick at Atlantic City. The idea that sediments are necessarily thickest where they are coarsest must be reversed for the coastal province; and we must recognize the essentially wedgelike character of the formations of this province in directions normal to the coast.

The upper and lower members of the entire coastal series are strongly, and the upper and lower strata of one and the same member are distinctly, divergent seaward and convergent landward. Apparently, then, this sphenoidal tendency may be set down as the dominant and specially characteristic structural feature of the province; and yet, where subaerial erosion has not intervened, conformity prevails throughout; for the successive beds are everywhere conformable, the cumulative lack of parallelism becoming appreciable only when a notable thickness of sediments has been traversed.

TERMINOLOGY OF CONFORMITY

For the wedgelike type of conformity which we have seen to be specially characteristic of the coastal province, *sphenoconformity* appears to be an appropriate name; and for a correlative term, applicable wherever the strata are approximately uniform in thickness and sensibly parallel throughout, or in the general view, *planoconformity* is suggested. Planoconformity may obtain locally on the continental platform, but must be regarded as specially characteristic of the abyssal ocean floor.

It is an interesting question as to the effect upon the conformity of strata of contemporaneous deformation. If the deformation take the form of a general tilting, sphenoconformity will naturally result, as we have seen. And plication, conceding the possibility of its surface manifestation, would, apparently, yield only a more localized sphenoconformity. Contemporaneous faulting, on the other hand, suggests *fractoconformity*, although it is doubtful if the

resultant structure would be markedly different from sphenoconformity; and essentially the same may be said for graben deposits.

GENERAL CONCLUSIONS

The Atlantic and Gulf coastal plain of the United States is believed to be a normal example of the coastal plains of the globe, and to be representative of the conditions under which, chiefly, sedimentary rocks have been formed in the past. The contact of the coastal plain sediments with the ancient floor or bed-rock surface on which they were deposited is everywhere the true and strongly marked clinunconformity of the Cretaceous peneplain. Above this peneplained floor, the coastal plain sediments are divided, landward, by repeated parunconformities developed during its progressive, oscillatory subsidence; while seaward they are apparently characterized through their entire thickness by the uninterrupted sphenoconformity indicative of continuous sedimentation, increasing in amount seaward or away from the source of the sediments owing to the constantly increasing divergence in that direction of its limiting planes—the Cretaceous peneplain and the surface of the sea.

When the coastal plain shall have been completed and its sediments, through the agency of deformation and metamorphism, shall have been added to the rigid crust these original structures will still persist. This entire body of post-Triassic sediments will be seen to be sharply limited downward by a strongly marked clinunconformity. Its original landward margin will be divided, as now, into a succession of terranes by an almost indefinite sequence of parunconformities, each the record of a complete crustal oscillation devoid of deformation; while throughout its more seaward portion, now largely embraced in the continental platform, the stratigrapher will be baffled by a blending sphenoconformity and a general absence of sharply defined stratigraphic boundaries.

NOTE.—Since this paper was written, my attention has been called to Arnold Heim's Monograph on "Die Nummuliten- und Flysch-bildungen der Schweizeralpen" (*Abhandlungen der schweizerischen paleontologischen Gesellschaft*, XXXV (1908), 173, in which he makes approximately, but not exactly, the same distinction between divergent and parallel uncomformity that is pro-

posed here, by introducing the term *Paenaccordanz* (penaccordance). His scheme thus includes:

Accordanz = conformity (strata parallel).
Discordanz = unconformity (strata divergent) = clinunconformity.
Paenaccordanz = approximate conformity (strata nearly parallel) = parunconformity.

Paenaccordanz is not, however, a perfect equivalent of parunconformity. It suggests a structural gradation, which, of course, actually exists; but it fails to emphasize the vital contrast between unconformity due to crustal deformation and unconformity due to crustal oscillation.

THE VALUE OF CERTAIN CRITERIA FOR THE DETERMINATION OF THE ORIGIN OF FOLIATED CRYSTALLINE ROCKS. II

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PART II

CHEMICAL COMPOSITION AS A CRITERION FOR THE DETERMINATION OF THE IGNEOUS OR SEDIMENTARY ORIGIN OF FOLIATED ROCKS

VIEWS OF OTHER WRITERS

It has long been well known that igneous rocks exhibit certain characteristic regularities in the amounts and proportions of their oxides, such as are not observed among sedimentary rocks. The composition of the latter is in part dependent upon the relative solubilities of minerals under weathering conditions, but also to a large extent upon the somewhat erratic redistribution of material during sedimentation. H. Rosenbusch[1] was the first to point out clearly the possibility of the application of chemical composition as a means of determining the original character of metamorphosed rocks. He considered that no important changes take place during dynamometamorphism because, first, many altered rocks possess a composition similar to that of certain normal igneous types and, second, on account of the preservation of clean-cut divisions between altered sedimentary strata of different composition. As a distinguishing feature between altered igneous and sedimentary rocks he pointed out that in the latter the molecular ratio of Al_2O_3 to Na_2O, K_2O, and CaO was greater than 1.

E. S. Bastin[2] has published the latest and most complete study regarding chemical composition as a criterion for the recognition of the original character of metamorphic rocks. From an examination of available analyses Bastin has determined certain distinguish-

[1] *Tschermak's Min. petrog. Mitt.*, XII (1891), 49.

[2] *Jour. Geol.*, XVII (1909), 445.

ing differences between the compositions of igneous and sedimentary rocks. His reasons for considering that the composition of a rock remains substantially unchanged during the development of foliation and that, consequently, it can be used as a criterion for the determination of the original character of a metamorphic rock are, briefly, based on the following: the application of criteria derived from normal igneous and sedimentary types to metamorphic examples whose origin has been established by other evidences and, second, instances in which the chemical compositions of both altered and unaltered rocks are known, a dike described by Teall[1] being used as an example. Bastin summarizes his conclusions as follows:

> Dominance of MgO over CaO is strongly indicative of sedimentary origin.
>
> Dominance of K_2O over Na_2O is of lesser critical value, but is nevertheless suggestive of sedimentary origin.
>
> The double relationship of dominance of MgO over CaO and K_2O over Na_2O affords very strong evidence of sedimentary origin.
>
> The presence of any considerable excess of Al_2O_3 in the analysis over and above the 1:1 ratio necessary to satisfy the lime and alkalies is also suggestive of sedimentary origin.
>
> High silica content may be indicative of sedimentary origin when supported by other criteria. This criterion must, however, be used with caution, since silication probably takes place in the dynamic metamorphism of certain igneous rocks.
>
> When three or all of the above relationships hold good, the evidence of sedimentary origin may be regarded as practically conclusive.

It is, perhaps, advisable to mention here that in the case of many, possibly in the majority of, igneous rocks either the MgO is in excess over the CaO or the K_2O over the Na_2O, a fact which Bastin recognized. The tables of Washington show that in the majority of igneous rocks containing over 70 per cent of silica the K_2O is in excess over Na_2O. Indeed it is not till the silica has dropped to less than 60 per cent that the dominance of Na_2O becomes marked. Accordingly, while the double relationship is, apparently, significant, the single ratios have but little value.

For some years C. K. Leith and W. J. Mead, of the University of Wisconsin, have had under consideration the possibility of marked changes in composition during the development of foliation in rocks.

[1] J. J. H. Teall, *Q.J.Geol. Soc.*, London, XLI (1885), 133.

It has been their opinion that the development of platy minerals as chlorite, sericite, etc., was the significant feature in the chemical changes, and that there is a tendency for constituents unnecessary for the formation of such minerals to be removed during the process of alteration. The evidence for this change in composition consists largely of the following: (*a*) field observations showing the development of schists from rocks which, on mineralogical grounds, would seem to have necessarily undergone a change in chemical composition during the formation of the metamorphic rock; (*b*) pairs of analyses representing the compositions of various unaltered rocks and the foliated derivatives from them. It is to be regretted that there are few such pairs of analyses available. Such as are known, however, indicate that rocks may undergo radical changes in chemical composition during the development of foliation.

An intimate knowledge of the field and chemical data outlined above as supporting the idea of change in composition during metamorphism would be necessary before their value as proof could be adequately discussed. The writer will, accordingly, confine his attention largely to the following occurrence with which he is personally familiar, but which has also been considered for some time by Dr. Leith and others to exemplify the chemical changes which a rock undergoes during the development of foliation.

THE ALTERATION OF QUARTZITE TO SERICITE SCHIST AT WATERLOO, WIS.

At Waterloo, Wis., there are exposures of a pre-Cambrian quartzite in which bands or lenses of a sericite schist have been developed. The quartzite has been described by many writers but J. H. Warner, while a student at the University of Wisconsin, was the first to study it with the idea of chemical change in mind. As a result of his investigations he concluded that the schist could have developed from the quartzite by a loss of silica without any introduction of material from the outside. He did not, however, dismiss the possibility of the schist representing argillaceous layers, or of part of the chemical differences between the schist and quartzite being due to the introduction of material from pegmatite dikes, such as are known to occur in one group of quartzite outcrops. The

work of the writer has been largely confined to the examination of the zircon and ilmenite contents of the rocks in order to obtain further evidence of chemical change during metamorphism. At the same time the rocks were studied in the field and under the microscope.

Data.—The quartzite exposures are not continuous but afford excellent opportunities for study, especially as a quarry has been opened up in one of the largest outcrops. Though the rock has been strongly folded, its bedding can generally be determined by means of conglomeratic layers. The schistose bands, which are seldom over two inches in thickness, may in some cases lie parallel to the bedding but in others they distinctly cut it.

The quartzite is of a dense crystalline type. It is predominately grayish in color, though vitreous and reddish phases also occur. Frequently specks of black iron oxide (ilmenite) and light-colored mica can be detected in the hand specimen. Under the microscope the fragmental texture can be recognized though the rock has suffered considerable granulation and recrystallization. Between the quartz grains are varying amounts of sericite and ilmenite with a few crystals of zircon. The sericite occurs in small flakes which are generally parallel to the borders of the quartz particles while the ilmenite is present in irregular grains. Sometimes the zircons are surrounded by quartz which seems, in some cases at least, to be of secondary origin.

The sericite schist is a uniform, fine-grained micaceous rock, generally of a pale greenish-yellow color. Under the microscope it is seen to consist of the same minerals as the quartzite except that the quartz has largely been replaced by sericite. In some places, associated with the sericite bands, are small stringers of quartz. The sericite flakes occasionally bend around portions of the quartz veins, suggesting that at least part of the quartz was present during the formation of the sericite.

The writer has separated the zircon and ilmenite grains from several specimens of the quartzite and schist by panning and the use of heavy solutions. It was found that the amount of ilmenite and zircon was in each case unusually large and that, apparently, both minerals were more abundant in the schist than in the quartz-

ite. Microscopic examination did not reveal any differences between the minerals present in the schist and those in the quartzite. The zircons from the two rocks are illustrated in Figs. 10 and 11. Many of the grains appear to be more or less rounded but in quite a number of instances the original outlines of the crystals can be seen. Some of the zircons may have remained in the quartz grains during sedimentation but the coating of iron oxide

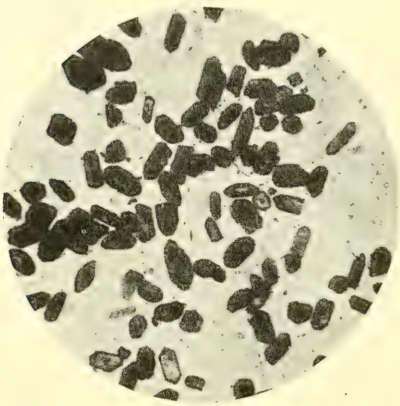

FIG. 10.—Zircons from quartzite, Waterloo, Wis. ×32.

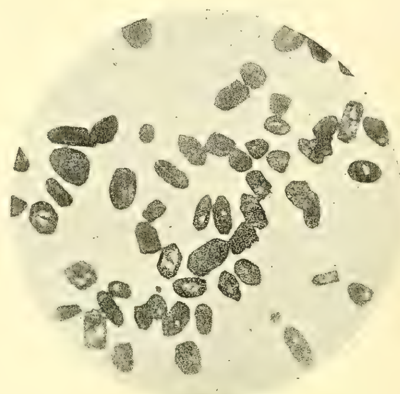

FIG. 11.—Zircons from sericite schist, Waterloo, Wis. ×32.

around practically every crystal seems to indicate that this was not generally the case.

The following analyses of material obtained by combining samples from three localities in the area were made for the writer by O. L. Barneby, of the University of Wisconsin.

	Quartzite	Sericite Schist
TiO_2	1.00	2.13
ZrO_2	.25	.45

These may be compared with the analyses of J. H. Warner. It must be remembered, however, that these pairs of analyses were made from different samples and one set cannot be regarded as the complement of the other.

Analyses by J. H. Warner

	Quartzite	Sericite Schist
SiO_2	86.60	58.61
Al_2O_3 & TiO_2	7.69	22.73
FeO, Fe_2O_3	3.72	9.73
K_2O	1.102	2.85
Na_2O	.508	1.18
Loss by ignition	.90	2.92

A test by panning made on material from a pegmatite dike in the quartzite some miles from the locality in which the schistose bands were developed did not reveal the presence of either zircon or ilmenite.

Conclusions.—The evidence showing that the bands of sericite schist are not altered argillaceous bands which may have undergone little change in composition during metamorphism may be summarized as follows:

a) Field evidence shows that the schistose bands are sometimes developed directly across the bedding. In many cases where they might be considered to have developed parallel to the bedding the schistose zones are lens shaped and cannot be traced to any argillaceous layer in the quartzite.

b) Zircon is usually formed only in igneous melts. During sedimentation the zircon grains become concentrated in the arenaceous beds and they are almost absent from argillaceous deposits. In the sericite schist, which has roughly the composition of an argillaceous sediment, zircon is present in amounts large even for arenaceous beds. It is decidedly in greater abundance in the sericite schist than in the quartzite.

c) Ilmenite is generally considered to form only under conditions of high temperature and it is usually associated with igneous rocks. There is no evidence that it has been formed secondarily in either the quartzite or the sericite schist. It is a heavy mineral and like zircon would be concentrated in the arenaceous beds during sedimentation, yet it is decidedly more abundant in the schist than in the quartzite.

The following evidences seem to indicate that the difference in

composition between the schist and the quartzite was not caused by the introduction of material from igneous intrusives.

a) There are no igneous intrusives known to cut the quartzite except pegmatite dikes several miles from the outcrops from which the samples of quartzite and schist were taken. These dikes do not appear to contain either zircon or ilmenite.

b) Neither zircon nor ilmenite are minerals which are known to develop in small grains throughout a contact rock. Neither mineral has a freshly crystallized appearance either in the quartzite or schist.

c) There are no minerals in the schist which do not occur to some extent in the quartzite.

The following points seem to show that the sericite schist has generally been developed from the normal quartzite by dynamometamorphism and that during the alteration there has been a large loss in material, probably mostly silica:

a) Both TiO_2 and ZrO_2 are distinctly more abundant in the schist than in the quartzite. The ratio of the increase in percentage is in each case approximately the same.

b) Warner's analyses show that the percentage of all other constituents except silica is greater in the schist than in the quartzite and that the ratio of the increase in amount is in each oxide, except silica, approximately the same.

c) Presence of quartz stringers associated with some of the bands seems to indicate that quartz was eliminated during the formation of the schist.

On an assumption of such a change in composition, as outlined, it is to be supposed that all gradations must exist between the normal quartzite and the most highly developed sericite schist. This affords a satisfactory explanation why Warner's figures seem to indicate a concentration of as high as 2.6 or even 2.9 while the more recent analyses of TiO_2 and ZrO_2 only indicate a concentration of about 2. It is to be hoped that a complete analysis of the two rocks will some day be available in order, that by comparison with the ZrO_2 and TiO_2 it may be possible to obtain more definite proof of the relative stabilities of the oxides during the alteration.

OTHER SERICITE SCHISTS WHICH HAVE PROBABLY ORIGINATED FROM QUARTZITE

It is interesting, at this point, to recall the case of the sericite schist described by Thürach[1] as containing abundant zircons. This rock is associated with the Taunus quartzite which also contains a large content of zircon. While the shale-like composition of the sericite schist may in large part be due to the original argillaceous character of the rock, it is possible that, to some degree at least, it results from a more silicious rock by a loss of quartz and a concentration of impurities.

More striking is a case described by Derby[2] in which there seems good reason for supposing that the sericite schist has a similar origin to that at Waterloo. Derby states that in appearance this rock is "*a purely micaceous rock with no evidence, even in the heavy residue, of more than the merest trace of free quartz and hematite*. . . . . The rock probably contains over 80 per cent of an iron bearing sericite with, perhaps, 7 per cent, more or less, of chlorite and a small percentage of quartz and earthy iron oxide. Washings reveal a small amount of secondary tourmaline, of which the grains appear to be secondarily enlarged, and *worn zircons of a size and abundance that seem extraordinary in a rock of such fine grain and of so purely argillaceous character*." The analysis of this sericite schist is given below in column 1.

	1	2
SiO_2	47.83	58.85
Al_2O_3	26.75	26.22
Fe_2O_3	8.51	3.01
FeO	.....	.17
MgO	2.43	.63
K_2O	10.42	8.44
Na_2O	.....	1.18
H_2O	.....	2.31
Ignition	5.33	.....

1. Schist found loose in the diamond mine of São João da Chapada, but presumed to come from a schistose layer in a conglomeratic quartzite.

[1] Würzburg, *Phys.-Medic. Gesellsch.*, XVIII (1884).

[2] O. A. Derby, *Am. Jour. Sci.*, 4th Ser., X (1900), 207–16.

2. Mesnard sericite schist. Column 2 represents the composition of the sericite schist which occurs at the base of the Mesnard quartzite in the Marquette district of the Lake Superior region. This has been recently described[1] as having been probably formed from quartzite by loss of silica, the other oxides being present in the same proportion in the two rocks. Tests made on these rocks by the writer showed that zircon, while present in each case, was not sufficiently abundant to enable conclusions to be drawn regarding chemical change during metamorphism.

THE CHARACTER OF THE CHEMICAL CHANGES DURING THE DEVELOPMENT OF FOLIATION

With regard to the nature and importance of the chemical changes which take place during the development of foliation it is only possible, at the present time, to indicate a few suggestions. Needless to say, the final composition is dependent on many factors, the principal of which are: the original mineralogical and chemical composition of the rock, the intensity and duration of dynamic action, the depth of burial and the proximity to igneous intrusions.

In the absence of igneous activity, the process of alteration seems to favor the production of a composition determined largely by that of certain platy minerals which are relatively stable under the conditions of differential pressure. The character of the platy minerals which form seems to depend to a marked degree upon the original composition of the rock, e.g., a talc schist appears to be the usual metamorphic product of a limestone as sericite schist is of a quartzite. In the case of the quartzite, by the way, the writer's observations suggest that with very intense metamorphism the sericite and iron oxide present in the less altered rock may combine, leading to the formation of a biotite schist much darker in color than the original.

To illustrate the variation in the amount and direction of chemical change for any oxide in the case of rocks of different composition, the SiO_2 content may be considered. The platy minerals mentioned in the last paragraph, being all silicates, have a somewhat limited range in the SiO_2 percentage. It is, accordingly, to

[1] *U.S.G.S. Mono.*, *LII* (1911), 257.

be expected that the SiO_2 content would tend to become lower or higher than that in the original rock, according as to whether the original SiO_2 lay above or below that range. This is illustrated in the following figure.

On the ordinate are plotted the percentages of silica, the composition of the original rocks being represented by circular signs, the white symbols representing quartzite, the shaded shale, and the black limestone. The crosses immediately above or below each

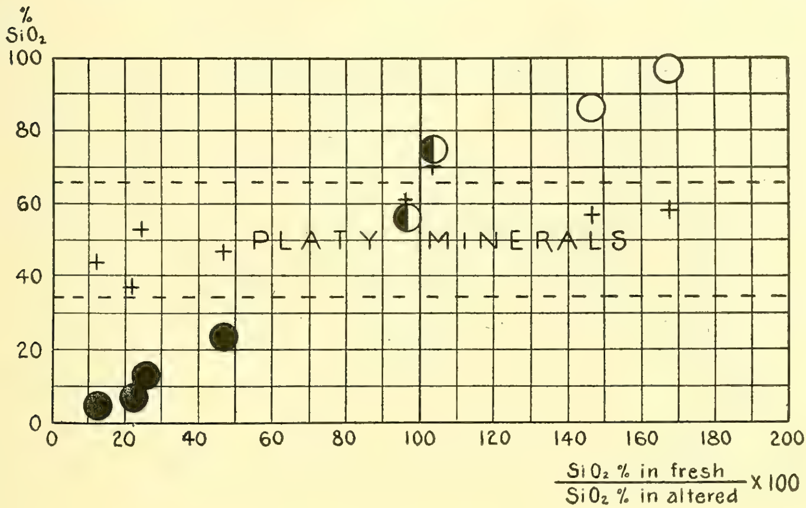

FIG. 12

of these signs represent the percentage of SiO_2 in the altered rock. Along the abscissa are plotted the ratios of the SiO_2 percentages of the fresh rocks to those of the altered rocks. For convenience the ratio is multiplied by 100 in the figures. Rocks appearing to the right of the 100 division show a decrease in silica percentage during alteration according to the distance which the symbol is from the 100 division, and similarly those to the left of the 100 division have gained in silica according to the distance of the symbol from the 100 division. The dotted horizontal lines include the approximate range for silica in the platy minerals. It is not to be supposed that the theoretical percentage is reached in any case though it is probable that those below the requirements have

generally gained and those above lost in SiO_2 percentage. As the preceding diagram is not intended to represent a tabulation of facts so much as to indicate one of the probable courses of chemical change, it has not been considered necessary to state the references for the rock analyses used, though the best available ones were employed.

In regard to other oxides than SiO_2, it seems that the platy minerals are, in general, characterized by low CaO and Na_2O content and they are generally high in Al_2O_3 and H_2O as compared with an average composition of igneous rocks. When these oxides are higher than the amount required to form platy minerals one might suppose from analogy with SiO_2 that they would tend to become partially eliminated during the development of foliation provided that they are in a soluble form. Available analyses indicate that such is the case. Further investigations are, however, needed before exact figures can be determined.

Near igneous intrusions the process of chemical change is probably generally different from that which takes place during dynamometamorphism, and the introduction of material from the magma may lead to a composition different from that which would be expected in the latter case. Possibly the resulting composition would be nearer that of an igneous rock in character.

CAN CHEMICAL COMPOSITION BE USED AS A CRITERION FOR THE DETERMINATION OF THE ORIGIN OF FOLIATED ROCKS?

The answer to this question can only be satisfactorily determined by careful chemical studies accompanied by close field observations. It will depend mainly on two factors: first, the character of the chemical changes as compared with the characteristic differences in chemical composition between igneous and sedimentary rocks, and, second, on the extent of the chemical change in large bodies of rock.

Regarding the first, it is to be noted that platy minerals are, as a rule, rather low in CaO and Na_2O and somewhat high in Al_2O_3, as compared with average igneous rocks. An increase of such minerals would seem to lead to a composition similar to the sedimentary type described by Bastin. An examination of analyses,

indeed, shows that practically all mica schists have, according to the criteria mentioned, the composition of sedimentary rocks. Probably the majority of such schists do represent altered sediments although some have been described[1] as originating from igneous rocks. It seems likely that if biotite in many igneous rocks were increased to 25 per cent, as was tested in the case of the Butte granite, with a corresponding decrease of other constituents, a sedimentary composition would be reached. Chlorite, which frequently forms the major part of some schists derived from igneous rocks also possesses a composition belonging to the sedimentary type rather than the igneous.

Less, even, is known of the extent of the chemical changes than their character, probably because it has not been generally held that rocks suffer significant chemical changes during the development of foliation. The sericite schist associated with the Mesnard quartzite is an important rock formation, and the chemical changes involved in its formation from a quartzite would be enormous. The writer is of the opinion that while chemical change during the development of sericite schist from quartzite is very striking, less marked changes probably take place more readily in igneous or argillaceous rocks since the latter types more readily undergo differential movement, a process which seems essential for the production of schistosity.

Proof of important changes in chemical composition during the development of foliation in certain rocks will not necessarily destroy the usefulness of chemical data as a criterion, though its limitations will become better recognized. The origin of igneous rocks which have not been greatly altered may, for example, possibly be recognized with some certainty from the chemical composition, since the process of alteration seems to tend toward that of the sedimentary type.

GENERAL SUMMARY

In the introduction to this article the writer has attempted to give a brief summary of the criteria which have been suggested for determining the origin of foliated crystalline rocks. These rocks

[1] E.g., A. Keith, *U.S.G.S. Folio 70*, 1901, p. 2.

may be divided into two classes: (1) those which received their foliation during consolidation from an igneous melt, (2) those in which the foliation is a secondary structure. Many geologists do not acknowledge the importance of the first group though gneisses have been described as such by many well-known writers. A review of the criteria for distinguishing these primary gneisses from metamorphic foliated rocks shows that the most significant distinctions are based on field observations. It has been frequently considered important to determine whether certain foliated crystalline rocks were originally sedimentary or igneous in character. Numerous field, microscopic, and chemical methods have been suggested for distinguishing these classes but it can hardly be claimed that the results of their application have been entirely satisfactory. The various methods proposed have been reviewed by the writer.

Three of the methods suggested for the identification of foliated crystalline rocks have been treated in the preceding article in some detail. They are: (1) the criterion of texture as applied to primary gneisses, (2) uses of zircon as a criterion (chiefly for distinguishing the original igneous or sedimentary character of rocks), (3) use of chemical composition as a means of determining igneous or sedimentary origin.

It seems plausible that primary gneisses, which are in reality only igneous rocks with a banded structure, could be distinguished from metamorphic rocks by means of texture. Grubenmann has made a careful study of the texture of metamorphic rocks and has proposed a rather complete system of nomenclature for the different types. This is being adopted by many German geologists but its introduction into English is rendered difficult by the conflicting meanings of "texture" and "structure" in the two languages. Grubenmann calls the texture characteristic of "crystalline schists" "crystalloblastic" and considers that it is distinguished from igneous texture largely by features caused by the simultaneous crystallization of the different minerals instead of the more or less successive crystallization common to igneous rocks. Milch, according to a recent article, seems of the opinion that texture will be found to be the distinguishing feature of

primary gneisses. Views regarding the mode of formation and the shape of certain minerals of primary gneisses have been discussed by the writer in order that the manner of the crystallization of these rocks may be understood. It has frequently been stated that the foliation in such rocks is due to the rotation of minerals in a still fluid magma. While this, no doubt, occurs in some instances the writer has endeavored to show largely by measurements of biotite grains that elongation of mineral constituents by crystallization under differential pressure must also be a very important factor in producing foliation. It is concluded that the typical texture of primary gneisses is more or less intermediate between the igneous and the metamorphic types but that owing to the conditions of formation of these rocks a crystalloblastic or even cataclastic texture may be superimposed on the original. Texture as a means of identifying primary gneisses seems, accordingly, of only limited application.

The suggestion that zircon be used as a criterion for the identification of igneous or sedimentary origin was made by Derby in 1891, but the method has not been adopted by many geologists. Zircons are widely distributed in igneous rocks and during sedimentation become rounded in form and concentrated in the arenaceous deposits. It is proposed that their presence and their character may serve as a means for determining the original character of foliated rocks. Essential to the application of zircon as a criterion is the question of its stability under metamorphic conditions. Derby was of the opinion that zircon could not form in a rock secondarily. The writer has shown by an example of secondary enlargement of zircon grains that this is not impossible. Other cases, however, appear to prove that zircon is sufficiently stable to be used as a criterion. The conclusions which seem justified regarding the use of zircon in this connection are briefly as follows: abundant, minute zircons in a rock indicates that the original rock was either igneous or an arenaceous sediment; when the grains are uniform in character, well crystallized, and fresh in appearance an igneous rock seems likely; when they are well rounded and lacking in luster the original rock was probably sedimentary; absence of zircon grains is confirmatory of sedi-

mentary origin but is only suggestive when other evidences are lacking; absence of zircon grains in quartzose layers indicates that such material is probably not of sedimentary origin but was deposited from solution; similarity in zircon grains may be used to establish the identity of altered rocks when the fresh types are available.

Chemical analysis has frequently been used as a means of determining the original igneous or sedimentary character of metamorphic rocks. Its use is based on the supposition that a rock, as a whole, undergoes no significant chemical change during the development of schistosity. C. K. Leith has recently suggested that such chemical changes may be important and are probably controlled by the composition of certain platy minerals. It has been his view that material unsuited for the formation of such minerals tends to become removed during the development of foliation. The proof of such chemical changes is largely based on, first, field observations which seem to show that in certain rock alterations there must have been changes in chemical composition on account of the mineralogical composition of the altered and unaltered rocks, and, second, pairs of analyses of fresh and altered rocks in which the proportion between the oxides necessary for the formation of the platy minerals have remained constant while the other oxides have usually decreased in amount in the altered rock. The writer introduces new evidence by the consideration of the percentage of zircon in fresh and altered rocks. Zircon, as has been shown before, generally remains unaltered during the development of foliation. The case of the quartzite at Waterloo, Wis., is discussed in some detail and it is shown, both by means of mechanical separation and chemical analysis, that the zircon content of the schist is much greater than that of the quartzite. Reasons are given for believing that the schistose bands do not represent argillaceous layers in the quartzite. The evidence of the zircon is supported by that of ilmenite which is also more abundant in the schist than in the quartzite. A short review of the mineral composition of platy minerals indicates that an increase of such minerals in a rock would lead to a composition belonging to the sedimentary type according to the criteria of Bastin. This

would, perhaps, seem to show that chemical analysis cannot be used satisfactorily as a criterion for determining original igneous or sedimentary character. It is probable, however, that composition may still be employed in this connection, to some extent at least, after the magnitude and character of the chemical changes involved in the production of schistosity in different rocks become better determined.

AN OCCURRENCE OF COAL WHICH BEARS EVIDENCE OF UNUSUAL CONDITIONS ACCOMPANYING ITS DEPOSITION[1]

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It is purposed to describe an occurrence of coal which is unique in its relationships to the overlying and underlying rocks and which shows by the structures in the associated sediments that it was deposited under conditions which were peculiar. Certain of these conditions differed widely from those which were usual to the accumulation of a continuous deposit of coal over a broad area, but it appears that certain other conditions which are suggested by the occurrence may have held during the accumulation of those coals which have been formed in the more usual manner.

THE OCCURRENCE

The occurrence is in a deep cut on the B. & O. Railroad at Sommerset, Perry County, Ohio. At either end of the cut a highly fossiliferous marine limestone is exposed, but throughout most of its length the bottom of the cut is not deep enough to reach it. This limestone, about 3 feet in thickness, is probably the Lower Mercer member of the Potsville formation. It is generally present in this region 75 or 85 feet above the base of the Pennsylvanian.

Above the limestone is a bed of soft gray clay shale which is some 12 to 15 feet thick. It is overlain by a massive coarse sandstone whose thickness is estimated at 20 to 25 feet. The upper part of the shale and this sandstone are exposed throughout the cut. The contact between them is very irregular, rising and falling as much as 6 or 8 feet. In pockets at this contact, well shown for 300 yards in the deeper part of the cut, the coal under consideration is found.

Above the sandstone there is a bed of shale 1 or 2 feet thick, overlain in turn by a second coal seam. Both of these are inacces-

[1] Published by permission of the State Geologist of Ohio.

sible. The upper seam is continuous and regular in thickness (perhaps 10 inches), so far as observation shows, from one end of the cut to the other.

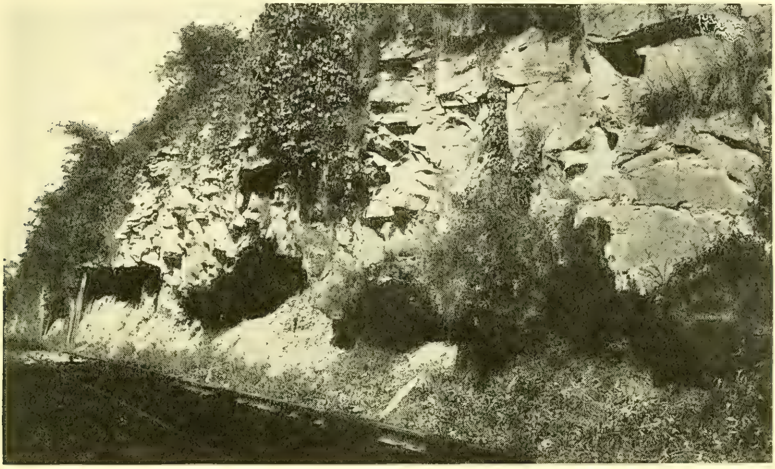

FIG. 1.—View of northwest side of the cut, showing the irregular base of the sandstone resting on soft shale. Four distinct shale crests each capped by a coal deposit (not visible) and four intervening sandstone-filled troughs with no coal are shown. The gentle inclination of the bedding (toward the observer) is wholly obscured by the irregular fracture faces of the sandstone.

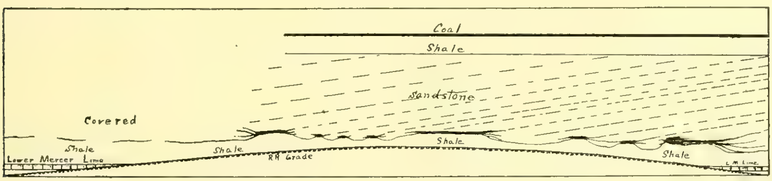

FIG. 2.—Idealized section of cut, showing relations of various members exposed. The vertical scale is much exaggerated, and the inclination of the sandstone is far too prominent. The structure near the top of the sandstone is not known. No attempt is made to represent the coal pockets at the base of the sandstone as they actually occur, although their general relations are correctly indicated. The thickness of these coal deposits is also overemphasized.

The massive sandstone and the upper coal seam can be traced for many miles in the region and seldom lose their identity. The coal seam at the base of the sandstone, on which interest centers

for the moment, if present generally, is seldom observed; the sandstone does not tend to form cliffs, and outcrops of this horizon are scarce.

The base of the sandstone which rests sharply either on the coal or on the shale when the coal is absent, rises and falls irregularly through several feet, and suggests strongly the existence of an erosion surface. This suggestion is supported especially by the distribution of the coal which is present only where the base of the sandstone is high, and disappears where it is low. It is not unusual to find coal seams overlain by a sandstone, which are thinner or wanting entirely in places because, as commonly expressed, the sandstone "cuts out" the coal. It has generally been supposed that such an interruption is due to erosion, and doubtless it is in some cases; but in the present one, this is not the correct explanation. At only one point, and that for but a few feet, is there any evidence of erosion, and even that is not conclusive in view of the irregularity found at all other points.

OCCURRENCE OF THE COAL IN POCKETS NOT DUE TO SUBSEQUENT EROSION BUT AN ORIGINAL CHARACTER

There are some 10 or 12 shale crests in the 300 yards which are clearly exposed, each with a bed of coal on the crest. In the sandstone-filled "troughs" which intervene there is no coal. The thickness of the coal, where present, varies from a fraction of an inch to 35 inches, rarely exceeding a foot. Horizontally, the coal may persist for only 2 or 3 feet on a small crest, or it may persist for 40 or 50 feet over a larger one. The sandstone troughs are of about equal width. But the coal is not truncated by the sandstone as it descends on either side of the crest. The coal seam splits and disappears on either side by interfingering with those portions of the sandstones which fill the "troughs." The seam may split abruptly into two or three thin streaks, and each of these in turn into as many or more within a few inches. Not infrequently two partings will reunite around a thick lens of sandstone.

There appears to be only one possible interpretation of the relation of the coal to the sandstone. The vegetable matter was accumulated in very limited patches, and coarse sands, sometimes

full of large and small plant fragments, were deposited simultaneously between these patches. The vegetable mud which later formed the coal was originally of about the same thickness as the intervening sands and was intertongued into them. Subsequently the vegetable mud was compressed to only a small fraction of its original thickness, but the sands were affected to a limited extent only.

AMOUNT OF REDUCTION IN THICKNESS OF ORGANIC DEPOSITS IN CHANGING TO COAL

Observations on several occurrences in the cut as to the relative amount of compression of the coal, as shown by the equivalent thickness of sandstone, give widely conflicting results.

	Thickness of Coal	Thickness of Equivalent Sandstone	Ratio of Coal to Organic Mud
1	3–4 inches	46 inches	1 to $11\frac{1}{2}$ to 15
2	$1\frac{3}{4}$ inches	30 inches	1 to 17
3	$\frac{1}{8}$–$\frac{1}{4}$ inches	15 inches	1 to 60 to 120
4	4 inches	20 feet	1 to 60
5	5 inches	31 inches	1 to 6*

* Thin coal streaks are prominent in the sandstone in the last case.

There are, however, certain factors which explain this variation in large part or entirely, although they do not allow a precise determination of the actual reduction in volume in the process of coal formation. In certain of these occurrences, there are many thin stringers of coaly material involved in the sandstone where its thickness was measured, and these also suffered reduction of volume, so that the thickness of sandstone given does not necessarily represent the original thickness of the adjacent column of plant mud. It cannot be said that these are more important in the first two instances and help to explain the relatively smaller thickness of sandstone there found; but they do explain in part the small thickness of sandstone in No. 5. As a matter of fact, the first two seem to indicate most nearly the actual reduction in thickness of the coal. There is a yet more uncertain factor involved in the inclined bedding of the sandstones, to be discussed below.

ADJUSTMENT OF THE SURROUNDING SEDIMENTS TO THE CHANGE IN VOLUME

At the time of the compression of the coal to its present volume or near it, some adjustment in the distribution of the adjacent sediments was necessary. This was accomplished, perhaps almost entirely, by flowage in the underlying soft clay shales, which slowly bulged upward beneath the coal deposits as their bulk became less, and came to form the shale crests which are capped by the coal. This is demonstrated by the fact that where thin sandstones are present in the shales, they are distinctly arched upward in these crests (Fig. 4). The sandstones over the coal are undisturbed except where they are interbedded with thin coals which have also suffered compression. On the side of one of the shale crests and in contact with the shale, they show flowage lines similar to slickensides, caused by the upward movement of the shale. There is evidence at one point that some of the movements of readjustment were abrupt; shales with a few thin sandstone beds are turned upward at a sharp angle for several feet so that their edges rest against the nearly horizontal bottom of the overlying main bed of sandstone. The bottom of the sandstone in this case carries the impression of the upturned thin sandstone layers of the shale series. These occurrences are believed to demonstrate that the massive sandstones were not consolidated at the time of the readjustment.

EFFECT OF INCLINED BEDDING IN DETERMINING THE AMOUNT OF REDUCTION

The most remarkable feature of the entire deposit is found in the inclined bedding of the thick sandstones, and in its relation to the coal pockets. The inclination of the bedding throughout most of the cut is toward the north and northeast, and usually at a low angle, commonly from 5° to 10°. At the south end of the cut the inclination is changed for a few yards to southeast. At the north end, just at the point where the outcrops become obscured by the low gentle covered slopes of the shallower part of the cut, the sandstones appear to have been derived from the northeast. The occurrence shown in Fig. 4 is found where the material from the two directions met.

For a distance of 120 yards, where the sandstones are persistently inclined to the north-northeast, the tongues which split off from the upper part of any one coal pocket toward the source of the material (that is toward the southwest) rise on the surfaces of the inclined bedding planes. This relation is best understood by reference to the accompanying sketches. It is this condition which, in part, makes uncertain the figures given above as to the relative thicknesses of coal and sandstone which accumulated simultaneously. The thickness of sandstone, except in No. 4, was obtained over the sandstone "trough" adjacent to the coal and represents the maximum over that trough, perhaps 10 or 15 feet from the coal. This is about as far as the thin coal streaks can be distinctly and readily traced (except in No. 5, where they are still present at the point where measured); but the bedding planes, which are continuations of these streaks, can be followed up the inclinations to the southwest until they are 15 feet or even 20 feet above the base of the sandstone. While in the outcrop there may be no reason to suspect a continuation of the coaly matter upward along the bedding plane, slight bruising of the stone with the hammer edge not infrequently yields a black stain, even when the beds appear to be in contact with each other. This thin film of carbonaceous material, rising many feet along the bedding planes, beyond the coal laminae, makes it difficult to determine just what thickness of sandstone is to be considered as formed simultaneously with the adjacent column of coal. The thickness given in all but No. 4 is that of the sandstones, which are somewhat irregularly bedded and lensed as a result of the thin streaks of coal and their compression, but measured as nearly as possible where there is no appreciable thickness of coal in the measurement. If measured farther away from the coal pocket, the thickness would be increasingly greater, but the sandstones, although carrying traces of carbonaceous matter on the bedding planes, would be regularly inclined and undisturbed by the compression, because the coaly matter was too thin to cause any appreciable readjustment in them. Furthermore, the thickness, when measured at the point usually selected, agrees fairly well with the heights of the shale crests above the base of the sandstone troughs; these are believed to be a rough

index of the amount of compression which has taken place in the coal.

However, the actual original thickness of the organic mud, and the exact amount of compression it has suffered, are only incidental to the subject under consideration, and are not at all essential to the interpretation of the associated structures.

POCKETS OF COAL NOT ACCUMULATED SIMULTANEOUSLY BUT SUCCESSIVELY

When one of the coal pockets splits into a number of thin layers, the layers spread out vertically through several feet of sandstones. These may or may not reunite to form the next adjoining coal pocket. More commonly they do not. The topmost coal parting on the side *toward* the source of the sands commonly rises with the rise of the bedding planes entirely above the coal pockets in that direction. On the other hand, the topmost parting on the side *away from* the source of the sands usually passes into the middle of the next pocket in that direction, or into its lower part or even entirely below the lowest stringer which comes from it. This is due to the gentle inclination of the sandstones.

This signifies an unusual method for the accumulation of the coal, if it is correctly interpreted. If the topmost and bottom-most stringers from two coal pockets are continuous from one to the other, no matter how far vertically they may diverge in the intervening sandstones, they are held to have been deposited simultaneously. On the other hand, if the top of one passes into the middle of the next one, the upper half of the latter is held to have accumulated after the former had ceased to form, or if the top stringer from one passes entirely beneath the bottom of the next one, the latter is held to have been wholly deposited subsequent to the former. These are the premises on which the conclusions rest.

When all of the coal pockets (nine in number) are considered in that portion of the cut where outcrops are entirely unobstructed and where the source of the material is persistently from the south-west, it is apparent that the one at the southwest end is the oldest, that is, the one nearest the source of the inclined sands. Further-

more, the deposition of each one of the nine was either begun later than that of its neighbor to the southwest, and was completed later,

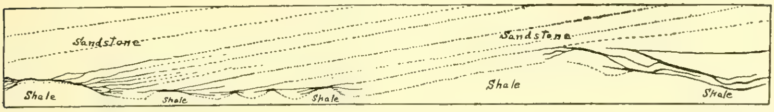

FIG. 3.—Generalized sketch of five of the crests and a portion of another, showing the relation of the coal deposits to the inclined bedding of the sandstones. Solid black lines, coal; dotted lines, bedding planes, usually with a black stain.

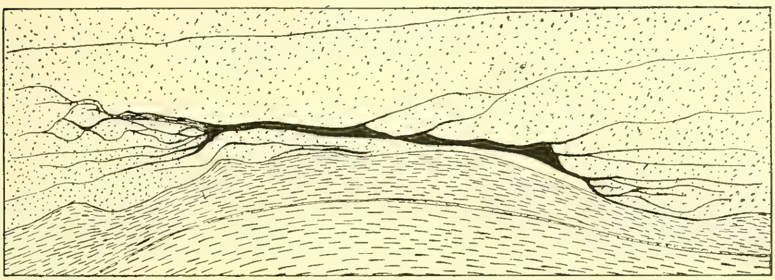

FIG. 4.—An occurrence of coal on one of the crests. In this case the sands were derived from both directions. Drawn correctly to scale from photographs and sketches.

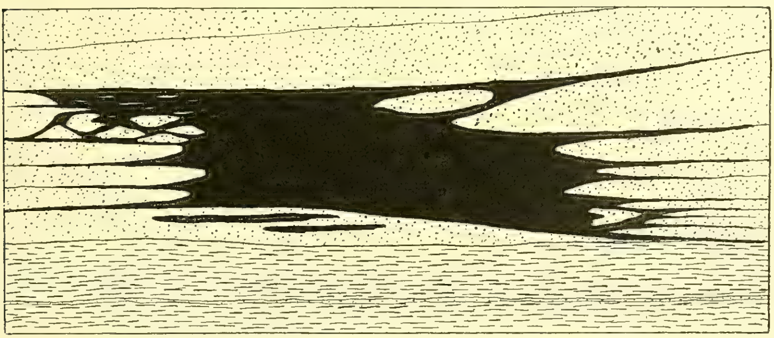

FIG. 5.—Ideal representation of the occurrence shown in Fig. 4, before compression.

or was begun entirely after this neighbor had been formed. Each pocket was formed at the toe of the advancing sand deposit, to be later covered and checked in its growth while a new deposit of

organic mud formed a few feet beyond where the edge of the sand had taken its new stand. The only exception to this statement is found in two adjacent beds which seem to have been formed simultaneously.

The coal deposits, although limited in cross-section, all have a lineal extent which is obliquely across the railroad cut and roughly parallel to the strike of the inclined beds of sandstone. This is so persistent that crests, troughs, sharp flexures, or even an unusually prominent split in a seam, features which may be only a few inches or two or three feet at most in width, can be recognized on both walls of the cut, and in the same succession. These are so regularly persistent that if the sandstones could be entirely removed over a wide area, the shale crests would appear as a series of roughly parallel ridges. The directions of ten of these features, selected because of their prominence, have been measured and all trend from northwest to southeast, although they vary through 40°. This directly supports the idea that they were accumulated along the edge of the sandstones as they advanced, delta-like, from the southwest.

There is but one feature for which no explanation is offered and which is not wholly in accord with the interpretation. In every case, there were sands accumulating immediately adjacent to the coal deposits and simultaneously on the side away from the source of the inclined sands. They are never thick and always have extended only a few feet beyond the deposit of coal mud. These muds were interfingered into them. What may be their significance, if any, is not known.

SUMMARY OF THE KNOWN FEATURES OF THE OCCURRENCE

To summarize the formation of the coal: It appears that it was not formed as a continuous deposit and subsequently cut up by erosion, nor were the pockets formed simultaneously in their present separated condition. It appears that the pockets were formed successively one after the other at the edge of the accumulating mass of inclined sand; that the vegetable mud accumulated to a thickness commonly of three or five feet (possibly 40 feet in the case of the 35-inch coal, although this seems excessive); that these

accumulations extended for considerable distances along the front of the sand deposit but only to a width of a few feet, and were intertongued with and accumulated simultaneously with the adjacent sandstones; that each deposit of coal mud in course of time was covered and its growth checked by the advancing sands while a new one formed a few feet beyond at the new edge of the sand, to be later covered in turn; that after the whole series had accumulated, the organic mud was compressed in the process of coal formation until its thickness was only about one-fifteenth its original thickness, and that the readjustment necessitated in the surrounding sediments by such local contraction was accommodated largely by the soft shales underlying the coal and sandstone.

It is worth while, also, to call attention to the general conditions at the time of formation of the deposit. The marine limestone, a few feet below the coal, is known to persist over two or three adjacent counties, and, if properly identified as the Lower Mercer, it extends over much of eastern Ohio and northwestern Pennsylvania. It marks a period of cessation from deposition of the sandstones and shales, with coals, which constitute most of the Coal-measures, and which, when fossiliferous at all, are only plant-bearing; it marks the prevalence of marine conditions over a large part of the northern Appalachian coal basin. The uniform thickness and character of this limestone bed indicate that it is the result of an abrupt subsidence which dropped the entire area far enough below sea-level to give open marine conditions. The phenomena caused by transgression and regression, resultant on a slow subsidence from above sea-level, appear to be entirely lacking. That open marine conditions, probably in shallow water, prevailed, is shown by the diversity of marine life forms present and the abundance of species and individuals which is commonly found, in central Ohio at least, at this horizon.

The limestone is succeeded abruptly in central Ohio by gray argillaceous shales between 10 and 20 feet in thickness—the shale below the coal seam under discussion. These quite commonly carry a marine fauna in their lower part. How rich this fauna is, is shown by the presence of 57 species from the shale at this locality in the collection of the writer's father, Mr. Eber Hyde. This

fauna is entirely absent from the upper part of the shale and it is evident that the typical marine conditions were excluded during the formation of the upper part, although there is no break discernible in the sediment and no evidence of shoaling in the shales.

The formation of the sandstones and of the coal bed marks the first resumption of typical Coal-measures sedimentation of the so-called continental type. The whole series suggests abrupt shoaling from shallow marine conditions and the dumping of sands, delta-like, into a shallow body of water, perhaps yet brackish but in which no marine organisms were living.[1]

WERE THE POCKETS FORMED BY GROWTH IN POSITION OR BY FLOATATION OF ORGANIC MATERIAL?

In what has been considered thus far, there is seemingly little room for speculation. The structures are distinct and the various relationships can readily be determined. Apparently, there is not a single conflicting feature, although some may be little understood. The interpretation given seems the only one possible, although certain conditions of coal accumulation are suggested thereby which are unusual, to say the least. However, these conditions probably have not obtained over any very great area and during the accumulation of none of the important seams. Certain other conditions seem to follow as a result of this interpretation, but in what remains to be said regarding these, there is less of certainty than in what has preceded.

Perhaps the most remarkable feature connected with the occurrence is the extreme localization of the deposits of organic mud. It is very curious that it should have accumulated along the foot of the sand slopes to the depth demanded, 5 feet more or less, but

[1] In this connection must be noted the finding in this railroad cut of a piece of coal with a well-preserved nautiloid shell in it, as yet, unidentified. The piece is entirely of coal and the fossil is preserved as an impression, the shell being wanting entirely. The piece was loose and it cannot be affirmed that it came from one of the coal pockets in the cut, as some coal is hauled through it from the Hocking Valley field. It is undoubtedly a case of a marine organism preserved in coal, but its source must be considered unknown, with a fair chance of its having been native to the cut.

should never, at any stage, extend more than a few yards outward from these slopes. This did not happen once only, but a number of times, and, furthermore, every time that there was any such accumulation, it was very limited. At first it was thought that the many thin stringers of pure coal ramifying through the sandstones with no evidence of "bottom clays" or old soil beds were evidence that the organic muds had been carried in suspension and dropped at the points where the coal is now found; if such had been the case, it is inconceivable that the mud would not have spread at each stage of mud deposition farther to the northeastward beyond the limit which was clearly set for it. What this limiting factor may have been is not apparent from the deposits themselves. As indicated earlier, sand at times accumulated to a small thickness on the side away from its apparent source, and plant muds were interfingered to some extent with this sand; but the coals disappear mostly by thinning within a few yards.

The best explanation for this narrow strip of organic mud extending along the margin of the inclined sands seems to be that it grew at the point where it is found, and that, at times, the growing plant beds spread out for short distances over the sands accumulating near by and thus became interbedded with them. The growing plants, on this assumption, were confined to the border of a shallow body of water and did not spread more than a few yards from the edge, although why they should not have spread over much more of the bottom which must have been just as shallow is not apparent. The water probably was not nearly of a depth equal to the thickness of the entire sandstone bed, since the coal is only interfingered with its base. In this connection, what the significance of the trace of black shale or coal extending up the bedding planes may be, cannot be said. It seems quite possible that the level of the water was a fluctuating one, standing low during stages of plant growth, and high at times of flood when the sands were brought in in large quantity.

It is not intended to imply that the rates of accumulation of both sands and muds, in so far as they accumulated simultaneously, were equal. On the contrary, the sand was probably dumped in

at intervals, when it would accumulate to a considerable thickness—several inches— in a short time. At these intervals it might bury a tongue of the plant mat which had spread out over preceding sands, but was often insufficient to cover the whole, and received a check, possibly from the plants themselves, that held it back of the main bed. As soon as an accumulation of sand buried the plants entirely at any one point, growth recommenced at the new margin. That there were frequently a number of such attacks by the sand which only covered thin extensions of the plant bed, is shown by the presence not infrequently of three or four or more beds of sandstone interbedded at the side of the coal, but not encroaching to any extent on its main body. Had the accumulation of the coal mud been due to deposition from suspension, it seems highly improbable that the sandstone incursions would have respected the unity of the deposit to any such degree.

The coal, too, in the main bodies and in most of the stringers is remarkably pure (ocular inspection only). Occasionally a thin clay parting is to be observed in undisturbed portions which is undoubtedly original in the coal, but these are so far absent, although to be expected in such accumulations as to negative further the suspension theory for the origin of the coal.

There is, however, no suggestion of a basal clay beneath the many thin stringers of coal which are found in the sandstone. Nor are there any of the characteristics of a basal clay or fire clay to be observed in the soft gray shale which underlies the coal deposits where they are thickest and without sandstone lenses, although these have usually been considered characteristic of growth of vegetation in place. However, the marginal swamp theory and the accumulation of the vegetable mud by growth in position is apparently a much more satisfactory explanation of the deposit as a whole than the flotation theory and is believed to be the correct one in this case. To say the least, the whole suggests very strongly that it may be possible for coal to be formed by growth in position, the time-honored conception of coal formation, without the development of an underclay full of root impressions, the presence of which has always been one of the chief facts in evidence to support this conception.

WHEN WERE THE DEPOSITS COMPRESSED TO APPROXIMATELY THEIR PRESENT THICKNESS?

There is yet another feature to be considered, the time when the reduction in volume of the coal mud occurred. Evidence has already been cited to show that this occurred while the sandstones were yet unconsolidated. As has been repeated, the accommodation of the surrounding sediments to this shrinkage was, in large part, by movement in the underlying shale. There was also some readjustment in the lower part of the sandstones, as shown by the irregular lenses between the coal stringers. But whether there was any very appreciable movement in the main body of the sandstone overlying the coal is not known. There must surely have been some. In one of the pockets, there are 12 to 14 inches of coal along a width of 60 feet, in another, 35 inches of coal are found in a rapidly pinching lens. Both of these cap unusually high shale crests, but it seems impossible, in these instances, that the thickness of vegetable mud necessary to form them, at the very least 15 feet, could have been compressed to its present state without allowing the overlying sandstones to settle slightly and irregularly. But the shale bed and coal which follow next above the sandstone are evenly horizontal and continuous and show no evidence of any such irregularity. This coal was formed as a sheet extending continuously over a wide area, and in a manner differing radically in detail from the one at the base of the sandstone. Its regularity in the cut is such as to suggest that equilibrium had been quite fully established in the underlying sediments before it was laid down although proof positive to this effect is not at hand. In other words, it is probable from the evidence furnished by this occurrence that some of the organic deposits which later formed the soft coals, perhaps all, were compressed nearly to their present volume very soon after accumulation. This loss of volume was probably chiefly due to the pressing out of the large quantities of water which must have been inclosed in the deposit at the time of accumulation. The loss of the volatile gases which marked the ultimate change to coal must have been accomplished more slowly, although it seems possible that a part of this, too, occurred at the time of this first loss. The not infrequent finding of coal pebbles

in Coal-measures rocks in such condition that they must have been coal at the time of their erosion—this too with no evidence of deep erosion of previously formed Coal-measures at any time during the accumulation of the whole—shows conclusively that the organic beds, within very short periods after their accumulation, had suffered most of the changes which resulted in the formation of coal from them.

THE GEOLOGY OF SOUTH MOUNTAIN AT THE JUNCTION OF BERKS, LEBANON, AND LANCASTER COUNTIES, PENNSYLVANIA

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INTRODUCTORY

The term South Mountain is applied in general to the range of high hills which enters the state of Pennsylvania from the east, extending in a southwest direction through the counties of Bucks, Northampton, Lehigh, Berks, Lancaster, and Lebanon, and thence, after a break, passing southwest through York, Cumberland, Adams, and Franklin counties into Maryland. It is a pre-Cambrian mountain range, the third or northern gneissic zone of Rogers, bounded on the north by the Paleozoic limestones and slates of the Great Valley, and on the south by the Trias. Several portions of the range, topographically prominent, bear individually the name of South Mountain and are so marked on the topographic maps issued by the United States Geological Survey.

The South Mountain of the title of this article is a ridge or elongated knob-like hill extending about nine miles east and west and four miles north and south, whose center is nearly at the junction of Berks, Lebanon, and Lancaster counties and near the intersection of parallel 40° 20′ north latitude and meridian 76° 10′ west longitude. It is nine miles west of the city of Reading and directly south of the Harrisburg division of the Philadelphia and Reading railroad. The villages of Newmanstown, Womelsdorf, Robesonia, and Wernersville lie in the Great Valley at its northern base. Fritztown is situated between the mountain and an adjacent hill on the east. Blainsport, Cocalico, and Kleinfeltersville respectively lie in the lowland to the south, southwest, and west.

The mountain crest is a divide between the drainage of the Schuylkill and the Susquehanna, streams flowing down the northwestern, northern, and eastern slopes reaching the former river via

the Tulpehocken and Cacoosing creeks; while the streams rising on the southern slope empty into Cocalico Creek whose waters eventually find their way to the latter river.

TOPOGRAPHY

South Mountain rises abruptly from the valleys on all sides and is isolated from the main chain at Reading. Its persistence as a topographic form is easily accounted for by the difference in hardness between its rocks and the rocks of the neighboring valleys.

The highest altitude, 1,340 feet, is attained in the northwestern part of the mountain at a point one mile southwest of Eagle Peak, being 964 feet above the level of the valley at Wernersville. South of here and a trifle east of the intersection of the county boundaries, the summit roughly presents the appearance of a plateau with a mean altitude of 1,100 feet, dissected by the narrow gorges of Furnace Creek in the north and an unnamed stream farther east. The summit is partially cleared of trees and farming is carried on to a limited extent. Eastward the height slightly decreases and the plateau-like character gives place to a number of knobs of which Cushion Peak is the most prominent.

West of Robesonia the northwestern part is a densely wooded ridge sloping steeply toward the valley with a low escarpment facing the interior. South of Wernersville the northern slope is cleared and is the site of several sanitariums.

The southern slope is more gentle than the northern, the stream courses are not as deep, and the streams are not as long.

Directly east of Fritztown, a ridge, 500 feet high and one-half mile wide, continues for over two miles eastward, finally merging into the valley. This ridge is very significant structurally as will appear later.

HISTORY

References to the mountain in geological literature are few, although Millbaugh Hill, as it was called, was known as early as the period of the Rogers Survey. H. D. Rogers,[1] in 1858 writes, "Westward a few miles from Reading there is an insulated tract of gneiss, forming, with the sandstone of Millbaugh Hill, an elevated

[1] Henry Darwin Rogers, *The Geology of Pennsylvania*, Philadelphia, 1858, I, 93.

district, the last of the chain of the Highlands. Between the Schuylkill and Cumberland County, this is the only representative of the South Mountains of our state. The tract is about nine miles long and two wide, and extends from the Cacoosing into Millbaugh Hill." The same writer[1] mentions the distribution of the Primal strata along the northern slope. The mountain's topographic and structural features were thus early recognized by this master observer.

D'Invilliers,[2] in 1883, mentions Millbaugh Hill in a number of places in his report upon Berks County, giving minor structural details but no full description of the mountain.

The existence of gneiss and Potsdam on the mountain is briefly noted by Lesley[3] in 1885, in summarizing the geological structure of the state.

If we turn to geological maps of the region a discordance of view is manifest. The writer has not seen the atlas accompanying the Rogers Survey reports. Our information is derived wholly from the maps of the Second Survey.

A map of Lancaster County,[4] published in 1878, shows the Triassic series covering the entire northern part of the county and contiguous parts of Lebanon and Berks.

A map of the Reading region,[5] published in 1883, includes only the eastern portion of the mountain at Cushion Peak, which is shown to consist of Potsdam sandstone cut by a large trap dike on the northern slope. Potsdam sandstone likewise covers the hill east of Fritztown and extends for some distance eastward.

In 1884 appeared a map of Berks County[6] which depicted the areal geology of South Mountain in a fairly accurate manner.

[1] *Ibid.*, 202.

[2] E. V. d'Invilliers, "The Geology of the South Mountain Belt of Berks County," *Second Geol. Survey Pennsylvania*, D 3, Vol. II, Pt. 1, 1883, vii, 50, 135–36, 204, 347.

[3] J. P. Lesley, "A Geological Hand Atlas of the Sixty-seven Counties of Pennsylvania," etc., *ibid.*, 1885, xxv, lxviii.

[4] Persifor Frazer, asst. geologist, "Grand Atlas, Geological Map of Lancaster County," *ibid.*, 1878; scale, 1 in. = 2 mi.

[5] "Geological Index Map to the Topographical Map of the Durham and Reading Hills or South Mountains," *ibid.*, 1883; scale, 1 in. = 2 mi.

[6] "Geological Map of Berks County, Compiled from the Surveys of F. Prime, E. V. d'Invilliers, R. H. Sanders, and Others," *ibid.*, 1884; scale, 1 in. = 2 mi.

According to the authors the central core consists of pre-Cambrian rocks bounded on the north, east, and west by Potsdam sandstone and on the south by the Trias. The above-mentioned trap dike at Cushion Peak is also shown.

The Hand Atlas,[1] in 1885, shows the main discrepancies above noted between the Berks and Lancaster county maps. The Lebanon County map shows Potsdam sandstone in the eastern corner.

The Lebanon County map,[2] issued in 1892, follows the Hand Atlas in regard to the distribution of the Potsdam.

According to the state map[3] of 1893, Potsdam sandstone covers the entire mountain and the hill east of Fritztown, and is cut by the trap dike at Cushion Peak.

GEOLOGY

From the preceding references it is evident that there has long been recognized on South Mountain an inlier of pre-Cambrian rocks surrounded by Cambrian sediments on the north, east, and west, and by Triassic sediments on the south.

The writer visited the region in the spring of 1911 accompanied by Mr. M. L. Jandorf of York, Pa. All available outcrops were studied. Exposures are of infrequent occurrence, however, owing to the covering of residual soil.

The boundary between pre-Cambrian and Potsdam on the west and northwest coincides with the foot of the eastward-facing scarp previously mentioned and the valley of a northern branch of Cocalico Creek. East of Eagle Peak the boundary extends in a straight line a trifle south of east for a distance of two and one-half miles bringing the pre-Cambrian down nearly to the level of the valley; thence following the base of the mountain southeastward and rising near the saddle west of Cushion Peak. From here it trends southwest for one and one-quarter miles, meeting the Trias at Laurel Ridge.

[1] "A Geological Hand Atlas of the Sixty-seven Counties of Pennsylvania," *Second Geol. Survey Pennsylvania*, 1885, scale, 1 in. = 6 mi.

[2] R. H. Sanders, "Geological Map of Lebanon County," *ibid.*, 1892; scale, 1 in. = 2 mi.

[3] A. D. W. Smith, "Geological Map of Pennsylvania," *ibid.*, 1893; scale, 1 in. = 6 mi.

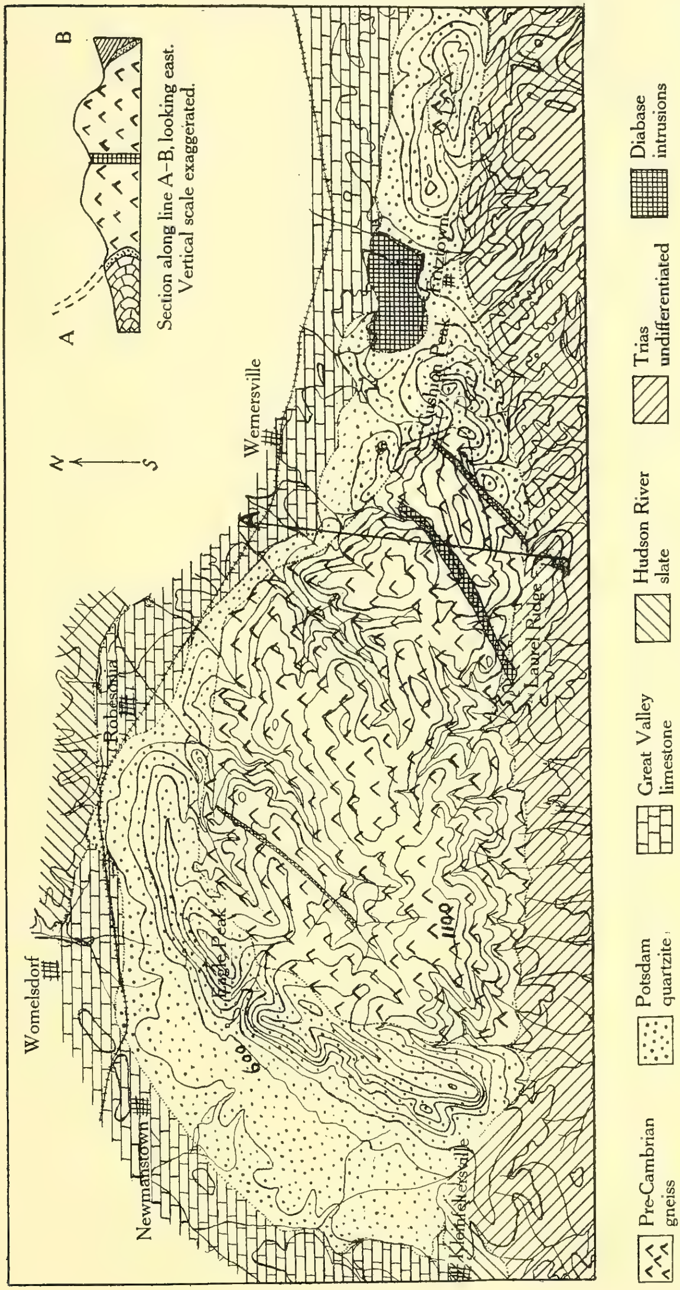

FIG. 1.—Geological map of South Mountain. Topography after U.S. Geological Survey. Contour interval, 100 feet. Scale, $\frac{1}{125,000}$

The pre-Cambrian-Triassic boundary from north of Laurel Ridge to Cocalico is approximately the southern base of the mountain. The distinct contrast in color between the lighter sandy soil of the one and the red soil of the other affords a means of accurate mapping in cases where only the decomposition products are available.

In the center of the hill east of Fritztown a small inlier of pre-Cambrian in Potsdam was found covering an oval area seven-eighths of a mile east and west by one-fourth of a mile north and south.

THE PRE-CAMBRIAN ROCKS

These comprise solid and basic gneisses cut by granite pegmatite in a complex similar to that occurring in the range at Reading and eastward. A study of thin sections shows the acid variety to be altered granite and the basic, mainly altered gabbro. From rather scanty field evidence the conclusion was reached that the granite gneiss is the younger of the two. Exposures showing the intrusion of one by the other are visible along the road and on both sides of the stream in the ravine directly southwest of the Insane Asylum. The direction of the foliation is N. 58° E.; dip 43° S.E. The close association of these two rocks is universal throughout the area, and no attempt has been made to differentiate them on the map. In general the gabbroic variety would appear to predominate in the east while granite gneiss is abundant in the western part.

Diallage is the ferro-magnesium mineral in the gabbro gneiss. A little hornblende, presumably secondary, also occurs. Magnetite is quite abundant.

Diorite gneiss covers a small area in the center of the mountain near the headwaters of Furnace Creek. Its relations to the other rocks are unknown, but it is believed to be of limited occurrence.

The granite gneiss is characterized by an abundance of alkali feldspar, more or less primary hornblende, an absence of biotite and a scarcity of muscovite.

Foliation is not marked in hand specimens of the gneisses, and in many slides can barely be detected with low magnification. The grain is uniformly medium.

These gneisses doubtless correspond very closely in composition

and age with the Losee, Byram, and Pochuck gneisses of eastern Pennsylvania[1] and New Jersey.[2]

Granite pegmatite occurs in isolated outcrops along the southern slope, and in the region of the valley southwest of the Insane Asylum. The exact manner of intrusion was not noted and no attempt was made to learn the direction of veins or dikes of this rock. Megascopically, the pegmatite is a coarse-grained binary granite composed of pink microcline and bluish quartz. That muscovite occurs sporadically in large bunches or pockets is evidenced by the abandoned workings of a mica mine situated on southwestern part of the plateau near the Lebanon-Lancaster county line.

PALEOZOIC ROCKS

Cambrian System; Potsdam Formation

The basal member of the Cambrian system is the Primal White Sandstone of Rogers, or the Potsdam Sandstone of the Second Geological Survey. On paleontologic evidence Walcott[3] correlates the Reading quartzite with the Chickies quartzite of Lancaster County, and with the quartzite of the South Mountain in York, Cumberland, and Adams counties. The same rock in Lehigh and Northampton counties is correlated by Peck[4] with the Hellam quartzite of York County, and the Hardyston quartzite of northern New Jersey.

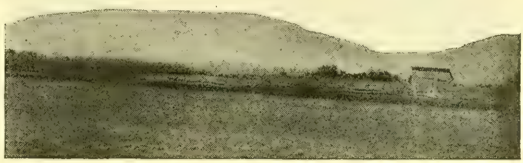

FIG. 2.—South Mountain from a distance of $1\frac{1}{2}$ miles, looking southeast from Newmanstown. The northern flanking ridge of quartzite is here shown. East of the notch it is known as Eagle Peak.

[1] Personal communication, by Dr. E. T. Wherry and Mr. E. L. Estabrook.

[2] H. B. Kümmel, "Geological Section of New Jersey," *Jour. Geol.*, XVII, No. 4, 1909, 352–53.

[3] C. D. Walcott, "The Cambrian Rocks of Pennsylvania." *U.S. Geol. Surv.*, No. 134, 1896, 29–33.

[4] F. B. Peck, "Basal Conglomerate in Lehigh and Northampton Counties, Pennsylvania," *Geol. Soc. Amer., Bull.*, XIV (1903), 521.

It is a hard, compact quartzite, usually white in color, weathering to white sand, and varying in texture from a rather fine basal quartz conglomerate to a whitish or reddish rock resembling jasper. Data for calculating the thickness of this formation on South Mountain are wanting. D'Invilliers[1] estimates the thickness around Reading at about 300 feet. Dr. Peck[2] assumes a thickness of 300 or more feet in Lehigh and Northampton counties.

The quartzite lies unconformably upon the gneisses and doubtless formerly covered the mountain, although south of the Eagle Peak ridge no vestiges of it now remain. The scattered outliers of this formation on the gneiss of the Reading hills attest its once universal extent throughout the region.

The greatest width of quartzite is roughly two and one-half miles measured eastward from the bed of Mill Creek north of Kleinfeltersville.

East of Newmanstown the northern boundary nearly coincides with the railroad track for a distance of three and three-quarter miles, the width of outcrop of the quartzite decreasing rapidly until at Robesonia barely one-half mile of the rock intervenes between limestone and gneiss. From Robesonia eastward the quartzite steadily narrows until directly west of the Insane Asylum its width for the distance of a mile cannot exceed one-quarter of a mile and at one point is scarcely 200 yards. Thence eastward the northern boundary maintains an easterly direction, passing one-half mile north of Cushion Peak and along the northern foot of the hill east of Fritztown. The width of outcrop west of Cushion Peak is one and one-half miles. A tongue of quartzite, one-half mile wide, extends southwest from Cushion Peak to Laurel Ridge where it is concealed by the Triassic cover. Potsdam is not seen along the southern border west of this locality. The width of outcrop east of Fritztown is about one mile, the southern boundary maintaining a general easterly direction.

Great Valley Limestone

The Potsdam quartzite is conformably overlain by limestone of the Great Valley series everywhere along the northern border, with

[1] *Op. cit.*, 102. [2] *Op. cit.*, 520.

one doubtful exception discussed below. As the limestone enters only indirectly into the present problem no further description of it will be given. Its Cambrian age has been shown by Walcott[1] and others.[2]

Ordovician System; Hudson River Formation

NOTE.—This formation in southern Pennsylvania is correlated with the Martinsburg shale of West Virginia by the U.S. Geological Survey.[3]

On the extreme western edge of the map at the village of Kleinfeltersville and near the Triassic border appears a small area of slates, being probably the eastern end of an inlier of the Hudson River formation mentioned by Lesley[4] and shown on the maps of the Second Geological Survey.

One-half mile west of Robesonia near the railroad a bluish slate lies either directly upon the Potsdam quartzite or in close juxtaposition. This is the southern limit of a belt of Hudson River slates according to the maps of the Second Geological Survey. Dr. Wherry[5] has frequently found beds of slate intercalated in the Cambrian limestones and thinks that the Second Geological Survey was in error in mapping as Hudson River certain slate areas in the South Mountain region. The question as to the age of the slate at this locality may be regarded as not yet definitely settled. The possible existence here of a strike fault of some magnitude, cutting out the limestones and bringing Hudson River and Potsdam in contact, is admitted, but data relative to any such dislocation are

[1] *Op. cit.*, 29–33.

[2] F. B. Peck, "The Cement Belt in Lehigh and Northampton Counties of Pennsylvania. A Description of the Geological Formations," *Mines and Minerals*, XXV, No. 2, 1904, 54; *idem, Econ. Geol.*, III, No. 1, 1908, 41.

G. W. Stose, "The Cambro-Ordovician Limestones of the Appalachian Valley in Southern Pennsylvania," *Jour. Geol.*, XVI, No. 8, 1908, 698–703.

H. Justin Roddy, "The Lower Cambrian of Lancaster County, Pennsylvania" (abstract), *Science*, N.S., XXX, No. 769, 1909, 415.

E. T. Wherry, "The Early Paleozoic of the Lehigh Valley District, Pennsylvania" (abstract), *Science*, N.S., XXX, No. 769, 1909, 416.

[3] G. W. Stose, "Mercersburg-Chambersburg (Pa.) Folio," *U.S. Geol. Surv.*, No. 170, 1909, 10.

[4] *Op. cit.*, lxviii.

[5] Personal communication.

wanting. From the fact that the slate is underlain by limestone in many places along the belt it would seem that the maps of the Second Geological Survey give the correct interpretation. The apparent unconformable overlap of the Hudson River slate upon the Cambrian formations is a point worthy of further study.

MESOZOIC ROCKS

Triassic System; Newark Series

The Newark is undifferentiated on the map. East of Cushion Peak basic igneous rocks of the diabase type form the southern boundary; westward the Newark rocks adjacent to the mountain consist of red basal conglomerate with quartzite pebbles and sandstone dipping gently south. The southern base of South Mountain was locally part of the northern border of the Triassic Sea.

Structure

Rogers[1] attributes the width of outcrop of the quartzite south of Newmanstown to "the presence of two or three anticlinal flexures." It was impossible either to verify or disprove this view during the present investigation. In the dense woods of oak and chestnut west of Eagle Peak outcrops are few and the above statement would seem to imply a hasty generalization from very meager data. One outcrop on the western slope of the mountain gave a strike N. 60° E., and a dip 70° N.W. Mr. J. H. Eby,[2] a mining engineer formerly of Mountville, Pa., states that the quartzite at Eagle Peak and farther west dips into the mountain. Whatever the truth may be concerning any minor undulations, the northwestern slope of South Mountain probably represents a steep upbuckling of the quartzite decreasing in dip toward the valley, with a possible slight overturn near the gneiss.

From Robesonia eastward the structure becomes more apparent, coincident with the narrowing of the quartzite outcrop. A short distance south of the Robesonia iron furnace the quartzite was observed to dip south into the mountain at an angle of 47° within

[1] *Op. cit.*, 202. [2] Personal letter.

a few hundred feet of the gneiss. Wherever limestone was observed near the quartzite from Robesonia to Wernersville and farther eastward, the dips were universally south toward the mountain. On the Insane Asylum grounds a large outcrop of limestone occurs near the quartzite where the latter is narrowest. The beds here are vertical.

One and one-quarter miles south of Wernersville quartzite overlies limestone in a quarry, both dipping 60° S. The patch of limestone at this point probably is an outlier on the quartzite of a few acres' extent along a synclinal axis, although the exact position of the quartzite-limestone boundary in this vicinity is in doubt, and the outcrop may possibly be on the boundary.

From the above facts it would seem probable that along the northern side of the mountain, particularly east of Robesonia, the Paleozoic sediments of the valley are overturned toward the north near their contact with the crystallines. This does not imply a great overlapping of the gneiss on the Paleozoics, and no fair interpreter could so construe the facts; but that, during the period of Appalachian folding when all the rocks were subjected to tangential pressure, the force acting from the south found expression in the northern part of South Mountain by an upward arching and slight overturn of the quartzite and limestone.

The possible existence of strike faults along the northern slope has been carefully considered but no evidence on this point was found. The writer is aware that certain geologists have demonstrated the efficacy of faults in bringing portions of the pre-Cambrian range above the Paleozoics of the Great Valley, but at the locality in question it would seem safer to give preference to the folding hypothesis until the region has been mapped in greater detail.

On the crest of the hill east of Fritztown the evidence in favor of overturning seems conclusive. The quartzite on both sides of the small pre-Cambrian inlier dips to the south. The structure of this hill thus epitomizes the structure of South Mountain.

In connection with the above interpretation it is instructive to note the observations in counties to the east of one long familiar with the same formations and general structural conditions. Dr.

Peck[1] found the quartzite overturned at one place, its beds dipping south toward gneiss.

He[2] has shown that the limestones in the Cement Belt have been overturned to the north and northwest in several localities to such a degree as to make probable a crustal shortening of 6 to 1.

The complicated structure of the South Mountain in York, Cumberland, Adams, and Franklin counties is generally conceded[3] to be due to overthrust faulting acting from east to west, bringing pre-Cambrian volcanics in contact with lower Cambrian quartzite. Within recent years, however, one observer[4] has described it as an anticlinorium with Lower Cambrian strata "in unbroken sequence" showing vertical or overturned dips on the northwest side. If the latter interpretation be correct, this mountain would seem to be similar, in major structural lineaments, to its smaller neighbor to the northeast described in the preceding pages.

DIKES

Three diabase dikes were traced for average distances of two miles, and others doubtless escaped observation. The general trend is northeast by southwest. The width of each can be inferred only approximately from surface float, being presumably but a few feet in the case of both the easternmost and westernmost dikes. The dike north of Laurel Ridge is the largest with a width of at least 200 feet. This dike cuts the Triassic conglomerate at Laurel Ridge, and thus its period of intrusion may easily be inferred. The dike rock is an olivine free diabase of fine texture. These

[1] F. B. Peck, "Basal Conglomerate in Lehigh and Northampton Counties, Pennsylvania," *Geol. Soc. Amer., Bull.*, XIV (1903), 520.

[2] F. B. Peck, "Geology of the Cement Belt in Lehigh and Northampton Counties, Pennsylvania," etc., *Econ. Geol.*, III, No. 1, 1908, 52–55; *idem, op. cit., Mines and Minerals*, XXV, No. 2, 1904, 56.

[3] C. D. Walcott, "Notes on the Cambrian Rocks of Pennsylvania and Maryland from the Susquehanna to the Potomac," *Am. Jour. Sci.*, 3d Ser., XLIV (1892), 477, 479–80; F. Bascom, "Volcanic Rocks of South Mountain, Pennsylvania," *U.S. Geol. Surv. Bull.* No. 136, 1896, 30; E. T. Wherry, "The Copper Deposits of Franklin-Adams Counties, Pennsylvania," *Franklin Inst. Jour.*, February, 1911, 153 (hypothetical structure sections).

[4] G. W. Stose, "The Sedimentary Rocks of South Mountain, Pennsylvania," *Jour. Geol.*, XIV, No. 3, 1906, 212, 216, 219–20; *idem*, "White Clays of South Mountain, Pennsylvania," *U.S. Geol. Surv. Bull.*, No. 315, 1907, 322–23.

dikes in the eastern part of the mountain possibly extend farther south and may be the northern portions of dikes depicted on the Lancaster county maps.

There is an oval mass of diabase northeast of Cushion Peak and north of Fritztown covering an area one and one-quarter miles east and west by one-half mile north and south. D'Invilliers[1] mentions a trap dike cutting the sandstone and limestone at this point, and infers a long northern extension of the same. Several of the above-mentioned maps likewise graphically express this view. This inference would seem to be erroneous, careful search failing to reveal the northeastern continuation of the igneous rock. This diabase mass is probably a boss of the same age as the dikes of the mountain.

SUMMARY

This study has aimed to emphasize the following points:

South Mountain structurally and topographically is a unit, its central core being an inlier of slightly metamorphosed acid and basic pre-Cambrian eruptives, flanked on the north by Cambrian sediments, and its southern base the local northern limit of the Triassic transgressional sea. During the Appalachian revolution the Cambrian quartzite, which may once have covered the summit, was up-arched and probably slightly overturned in the northwestern part of the mountain, while in the northeastern part it was overturned upon the limestone of the Great Valley. The Triassic sediments along the southern base of the mountain show a slight tilting to the south. The diabase intrusions cut the Trias, and presumably belong to the same period of eruptive activity whose evidences are so common elsewhere throughout the East. The physiographic prominence of the mountain is due to the superior hardness of its rocks.

The writer's sincere thanks are due to Mr. Eby for the contribution of valuable data. Dr. M. E. Wadsworth, of the School of Mines, University of Pittsburgh, and Dr. C. R. Eastman, of the University of Pittsburgh and Carnegie Institute, have aided in suggestions; Mr. Jandorf has ably assisted in the field; and Dr. Wherry and Mr. Estabrook, of Lehigh University, have helped in correlation.

[1] *Op. cit.*, vii, 204.

MURAENOSAURUS? REEDII, SP. NOV. AND TRICLEIDUS? LARAMIENSIS KNIGHT, AMERICAN JURASSIC PLESIOSAURS

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The material upon which this paper is based consists of the more or less fragmentary remains of two plesiosaurs from the Jurassic of Wyoming, furnished by Professor Wm. H. Reed, curator of vertebrate paleontology in the University of Wyoming. It is in honor of Professor Reed that the name *Muraenosaurus? reedii* is given to one of the species which proves to be new.

Muraenosaurus? reedii, sp. nov.

This specimen consists of a fairly complete right coracoid and a part of the left one, parts of the right and left pubes and ischia, numerous dorsal and caudal vertebrae, several ventral ribs, and a nearly complete left pectoral paddle. The species, judging from the remains at hand, is one of the most primitive found in America and in all probability belongs to a new genus. The material is hardly complete enough for a generic description, however, and the species is therefore provisionally placed with the English genus *Muraenosaurus* Seeley,[1] which it closely resembles in several respects. The primitive form of this species is shown in the relatively long humerus with its moderately expanded distal end, the long radius, and the relatively small degree of hyperphalangy. Although there is no way of determining the length of the neck, it must have been long, for the ischia are short and the association of these two things, long neck and short ischia, seems to be a rule that can usually be depended upon. The similarity of this species with *Muraenosaurus* will be seen in a comparison with the following partial diagnosis of that genus by Andrews:

In the shoulder-girdle there is a well-developed interclavicle, while the clavicles are generally greatly reduced, in some cases being mere films of bone

[1] Andrews, *Marine Reptiles of the Oxford Clay*, Part 1, p. 77.

adherent to the visceral face of the interclavicle; in some cases probably they are wanting entirely. Coracoids not greatly produced outward and backward into postero-lateral processes. Fore limb a little larger than the hind limb, to which it is very similar in form, the humerus not being greatly expanded at its distal and even in the adult.

The coracoids, shown in Fig. 3*a*, are strikingly short, and although the posterior border is missing, they are so thin at this point that nearly the entire bone is probably represented. The anterior border is considerably thickened and in the median line extends forward in a short, obtuse angle which apparently did not articulate with the scapulae. In general form they resemble *M. durobrivensis* Lydekker. They have a width of 310 mm. and are 260 mm. along their greatest length.

The pelvic girdle is represented by a part of the left pubic bone from the acetabulum to the median line, the lateral end of the right pubis, and the acetabular extremities of the ischia. From these the details of the girdle cannot be obtained, but the parts present resemble closely those of the above-mentioned species.

The ventral ribs (Figs. 3*b*, 3*c*, and 3*d*) are peculiar on account of their massiveness: they greatly exceed those of all other known American forms in size, so far as I can learn, and in that respect resemble those of the English forms *Muraenosaurus*, *Cryptocleidus* Seeley, and allied genera. The median ribs are not uniform in shape or size, those present ranging from 18 mm. to 30 mm. in thickness and from 30 mm. to 37 mm. in width. Some of them reach a length of at least 560 mm. The extremities are flattened for a considerable distance along the ventral surface for the articulation of a row of smaller lateral ones. The number and arrangement of these ventral ribs cannot be determined, but it was probably much the same as that in *Cryptocleidus* and *Muraenosaurus*, viz., a median and three overlapping lateral rows.

The vertebrae are somewhat crushed and badly weathered and cannot be described with a great deal of accuracy. There are thirteen dorsal vertebrae present, all of which have the spines missing as well as most of the arches. The centra are moderately biconcave. They are somewhat flattened on the ventral surface, the lateral surface, however, being rather deeply concave antero-

posteriorly. Not much can be said of the arch except that it is apparently low, the diapophyses arising just above the centrum. The diapophyses are rather stout, directed outward in a horizontal plane, and have an oval cross-section the greater diameter of which is directed in an antero-posterior direction. The centra vary between 33 mm. and 40 mm. in length and are but slightly wider than long. Of the fifteen caudal vertebrae present two are from the posterior region and are disklike, cylindrical, and flattened on the articular surfaces. The other thirteen caudals are more anterior in position, from round to oval with flattened ventral surface in cross-section, moderately biconcave, the lateral surface concave antero-posteriorly. The diapophyses arise low down on the centrum nearly on a plane with the ventral surface and directed out and downward. The lower articular borders are slightly beveled for the chevrons. In length the centra range between 21 mm. and 26 mm. and from 33 mm. to 36 mm. in width.

The left pectoral paddle, with the exception of the ulna, a supernumerary mesopodial, a supernumerary epipodial, perhaps, and a few phalanges, is excellently preserved. A comparison of the paddle of this species with that of *Muraenosaurus leedsi* Seeley (Figs. 1*a* and 1*b*) shows the similarity of these two forms. *The humerus* is relatively long and slender, the shaft is oval in cross-section, tapering gradually from the distal expansion nearly to the proximal extremity. Here it expands sharply on the inner radial side into the head with a similar but less sharp expansion on the opposite side of the shaft. A broad shallow grove on the inner and outer sides of the shaft separates these two expansions into head and tuberosity which lie in a plane twisted at an angle of about forty degrees with that of the distal expansion. Along the upper third of the radial margin of the shaft there is a well-marked ridge, which loses its identity, however, in a short distance both proximally and distally. About 65 mm. below the head there is a strong ridge, for the attachment of muscles, running up and backward on the inner surface of the shaft. The distal end is moderately expanded and shows articular facets for the radius and ulna, the former measuring over half the width of the expansion, the latter a little less than one-third. Although there is no facet for the articulation

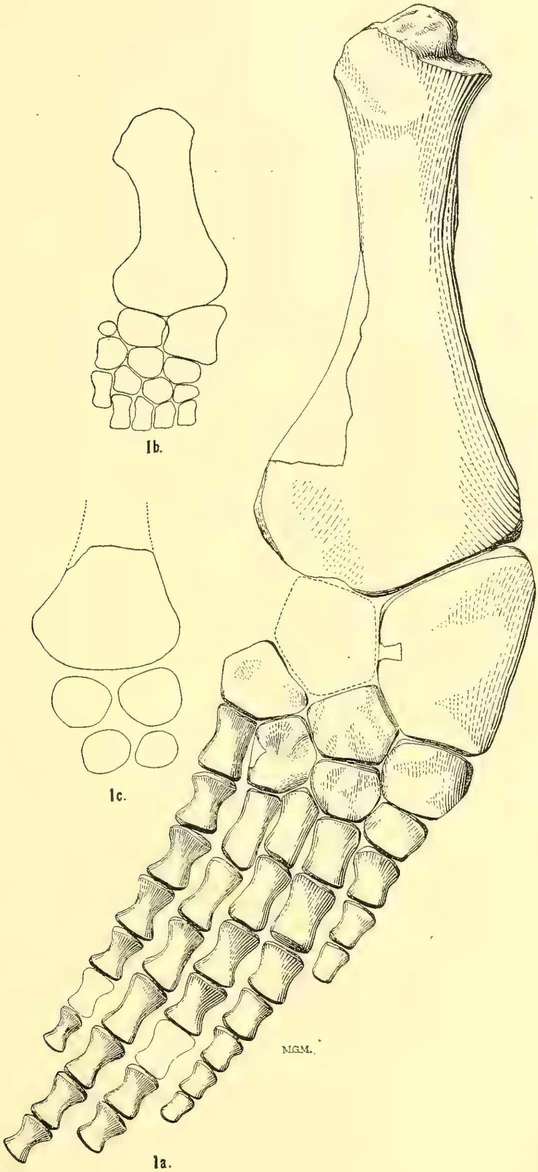

FIG. 1.—1*a*, left pectoral paddle of *Muraenosaurus reedii*, $\times \frac{1}{4}$. 1*b*, *M. leedsi* Seeley, pectoral paddle, $\times \frac{1}{10}$. 1*c*, pectoral paddle of *Pantosaurus striatus* Marsh (after a photograph by Williston), much reduced.

of a supernumerary epipodial, such a bone was probably present to fill out the remaining width of the humerus. *The radius* is remarkable for its length, being longer in comparison with its width than in any other known American form. Its greatest length is along its somewhat thinned outer margin. From here it gradually thickens toward the inner side and toward the extremities. The inner face is apparently unnotched and shows a close articulation with the ulna. *The ulna*, though not known, must have been pentagonal and considerably smaller than the radius. *The carpus* is represented by six bones, three in the proximal and three in the distal row. The ulnare has an articular facet on the outer upper surface, however, showing the presence of a fourth element in the proximal row. *The fingers* are not greatly elongate and are primitive in their relatively small degree of hyperphalangy. The arrangement of the bones is based partly on the determination of Professor Reed and partly on their relative size and shape. For this reason it cannot be said with certainty that the arrangement or number is correct. According to this determination there are, beyond the metacarpals, two phalanges in the first and six in the second finger, with a terminal phalanx missing in each, perhaps. There are five phalanges present in the third finger, with the fourth missing. In the fourth finger there are six and in the fifth five, with number five lacking. In each of the third, fourth, and fifth fingers there are probably two or three terminal phalanges missing.

A brief comparison with other American Jurassic forms will serve to bring out the distinctive characters of this species:

Comparison of the paddle with the outlines of that of *Pantosaurus striatus* Marsh (Fig. 1*c*), taken from a photograph of the type specimen made by Dr. Williston, shows a marked difference; the radius and ulna in this form are both short, and about equal in length and width.

The description and figure of *Megalneusaurus* Knight, of which *M. rex*[1] is the type, shows the difference between these two forms. In *M. rex* the ulnar articular facet of the humerus is convex, the radius and ulna are short and of about the same dimensions, a radio-ulnar opening is present, and there are but three bones in the proximal row of the carpus.

[1] *Am. Jour. Sci.*, V, 378, Fig. 1.

It is improbable that the Jurassic plesiosaur *Plesiosaurus shirleyensis* Knight[1] belongs to the genus *Plesiosaurus*.[2] The vertebrae,

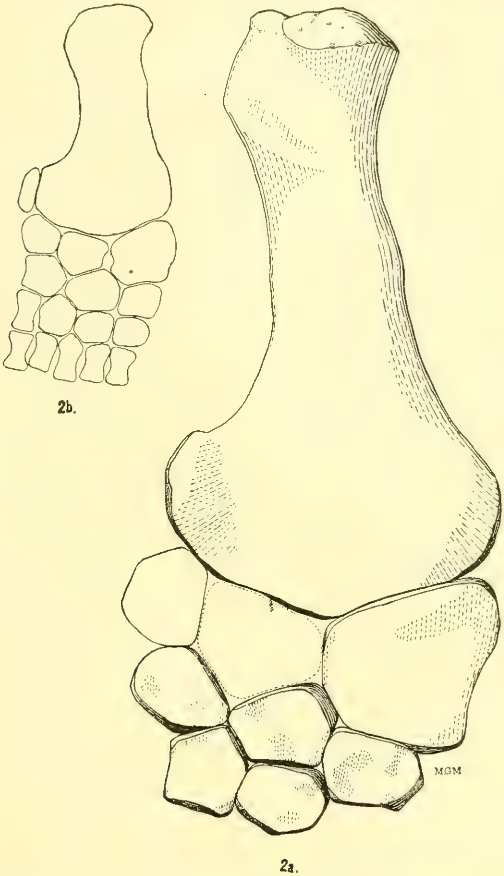

FIG. 2.—*Tricleidus* Andrews. *2a*, left paddle of *T. laramiensis* Knight, $\times\frac{1}{4}$. *2b*, pectoral paddle of *T. seeleyi* Andrews, $\times\frac{1}{6}$.

however, seem to separate *M. reedii* from this form. Quoting from Professor Knight's description of *P. shirleyensis:*

The vertebrae are slightly biconcave, and all wider than long; but in the dorsals and posterior cervicals the length and breadth are nearly equal. . . . . On the anterior caudals the neural spines are of considerable height. Nothing

[1] Knight, *Am. Jour. Sci.*, IV, 115.

[2] S. W. Williston, *North American Plesiosaurs*, Pub. Field Columbian Mus., Geol. Series, II, No. 1, p. 7.

of importance is known of the dorsal vertebrae, excepting that they are slightly biconcave and circular in transverse sections. Anterior caudals are flattened beneath and have two large circular facets for the articulation of the chevrons; neural arches firmly attached to centra.

The type material of *P. shirleyensis* is so fragmental that one cannot be certain of the distinguishing features.

Tricleidus? laramiensis Knight

The following description is based on a part of the original specimen described by Knight as *Cimoliosaurus laramiensis*.[1] In the past *Cimoliosaurus* Leidy has been made a sort of catch-all for the remains of imperfectly known plesiosaurs. The genus, however, was described from vertebrae alone[2] and, therefore, till it is better known, a species can be referred to it with certainty only on evidences furnished by the vertebrae. In Leidy's description of the type, *C. magnus*,[3] he figured what he took to be two dorsal and eleven lumbar vertebrae. I believe that Dr. Williston was right, however, when he referred Figs. 13–19, Pl. 5, in Leidy's description, to the cervical region, Figs. 1–5, Pl. 6, to the dorsal, and Figs. 6–19, Pl. 6, to the cervical region.[4] The caudals of *Discosaurus* Leidy, described in the same work, along with *Cimoliosaurus* and later shown by Cope to be identical with that genus, have a pair of ridges extending antero-posteriorly along the ventral surface. The vertebrae of *Cimoliosaurus*, then, have certain generic characteristics, but none of these is mentioned by Professor Knight in his description of *C. laramiensis*. In fact, the only characteristics mentioned are "the forward overhanging" of the dorsal centra and the large angular chevron facets of the caudal vertebrae and neither of these is noted in the type specimen. Furthermore, *Cimoliosaurus* is typically an Upper Cretaceous form. The species here described is, therefore, provisionally placed with the English genus *Tricleidus* Andrews,[5] the pectoral paddle of which is very

[1] *Am. Jour. Sci.*, IV, X, 117.

[2] *Proc. Nat. Acad. Sci. Phila.*, 1851, 325; 1854, 72; pl. 2; figs. 4, 5, 6.

[3] *Smithsonian Contributions to Knowledge*, XIV, 25–29; pl. 5; figs. 13–19, and pl. 6; figs. 1–19.

[4] *Am. Jour. Sci.*, XXI, 222.

[5] Andrews, *Marine Reptiles of the Oxford Clay*, Part 1, p. 149.

similar. A comparison with the description of the following salient features of *T. seeleyi* Andrews will show the similarity of these two forms.

The fore limb is peculiar in several respects and differs considerably from that of *Cryptocleidus* and *Muraenosaurus;* its most striking characteristic

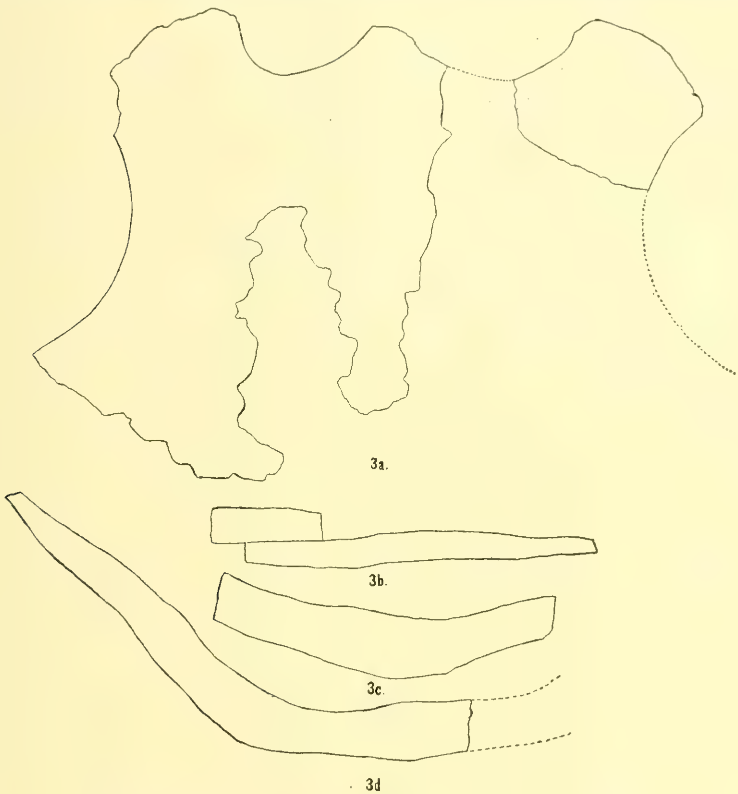

FIG. 3.—*Muraenosaurus reedii.* *3a*, coracoids, *3b*, lateral ventral ribs, *3c* and *3d*, median ventral ribs, all $\times\frac{1}{4}$.

is that the humerus articulates distally with four bones—three, the radius, ulna, and pisoform, being large, the fourth a small postaxial accessory ossicle. *The humerus* is short and stout; the head is round in outline and convex; at its upper anterior border it is continuous with the surface of the strongly developed tuberosity. This is bounded both in front and behind by strong ridges, which extend down a little on the shaft; its upper surface is flattened, and a little below its upper border there is a well-marked rugosity for the

attachment of muscle. The stout shaft is oval in section; its anterior border bears a roughened ridge, and the upper part of its ventral and ventral-posterior surface is roughened for muscle attachments. Distally the bone is expanded and compressed from above downward. The facet for the radius is the largest, that for the pisoform the smallest; the surface of the accessory ossicle is situated entirely on the postaxial border nearly parallel with the long axis of the bone.

The material at hand consists of the left humerus, the radius, five carpals, and a sixth bone which is probably a supernumerary epipodial. To the description of the humerus by Professor Knight it might be added that the plane of the distal expansion forms an angle of about fifty-five degrees with that of the head and tuberosity and that there is an articular face on the posterior distal end for the articulation of a third bone and perhaps a fourth facet on the posterior face of the expansion. The arrangement of the carpal bones is quite certain, there being three in the proximal row and two in the distal row, with a third, the first distal carpal, missing. A sixth bone, the position of which is uncertain, is represented in the figure by an unshaded outline as articulating with the humerus and the third carpal in the proximal row. There seems to be a distinct facet on the humerus and carpal at these points and in all probability the bone represents a supernumerary epipodial.

One of the most striking resemblances between the two forms is seen in the posterior border of the humerus; in each the distal expansion is recurved posteriorly, and although the fourth bone found articulated with the humerus of *T. seeleyi* is absent in *T. laramiensis*, the posterior border of the humerus suggests that such a bone was originally present though perhaps not thoroughly ossified. A comparison of Figs. 2*a* and 2*b* shows this likeness.

I take this opportunity to acknowledge the kindness of Professor Reed in granting me the privilege of studying this material and also to thank Dr. Williston for suggestions in the preparation of this paper.

METAMORPHIC STUDIES

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INTRODUCTION

The early study of rock metamorphism consisted principally in the aggregation of a vast mass of more or less unrelated observations on rock alterations. Much of the literature on metamorphism has been so technical and so purely descriptive that it is natural that the general reader tends to postpone serious consideration of the subject. In recent years notable attempts by Van Hise,[1] Grubenmann,[2] and others have been made toward systematizing the subject and making it more available. Their works, especially that of Van Hise, are epoch-making and must necessarily be in the hands of the student of metamorphism. Later study has been more along quantitative lines and has resulted, as would be expected, in clarifying some of the principles, and in a better understanding of their significance. There seems to be need now of a more elementary treatment of metamorphism, shorn of some of the less essential details, and including recent quantitative developments which would be more widely used were their significance understood. This series of articles is an attempt to meet this need. Quantitative results, usually expressed graphically, will be used as a basis for the development of the principles of metamorphism. In the first article the general significance of the metamorphic cycle is discussed, as preliminary to a more detailed consideration of metamorphism.

THE METAMORPHIC CYCLE DESCRIBED[3]

The keynote of rock alterations is adaptation to environment. A molten rock or magma enters the outer shell of the earth and

[1] C. R. Van Hise, *A Treatise on Metamorphism*, Mono. 47, U.S. Geological Survey, 1903, pp. 1286.

[2] Dr. U. Grubenmann, *Die kristallinen Schiefer*, Part I, 1904; Part II, 1907. Berlin.

[3] C. K. Leith, "The Metamorphic Cycle," *Journal of Geology*, XV (1907), 303–13.

comes within our range of observation. No sooner does it crystallize than changes begin—with great rapidity nearest the surface, with less rapidity below. These changes are both chemical and physical. Water, carbon dioxide, oxygen, and other substances of the hydrosphere and atmosphere attack the rocks. The ferrous iron of the igneous rocks combines with oxygen and water and a large part of it remains as residual limonite. Alkalies and alkaline earths form soluble salts and are leached out in well-determined order. Free quartz is less readily changed or dissolved. The portions of the bases which the waters have failed to abstract tend to remain combined with alumina and silica, taking on water to form new hydrous silicates, although some of them may remain in place as carbonates or other salts. The excess of alumina and silica left from the leaching out of the bases from silicates becomes hydrated and forms clay. There are ultimately left, then, iron oxide, quartz, clay, and a variety of hydrous aluminum silicates, characterized by a lower ratio of silica to the bases than in the original silicate minerals. Oxide zones of ore deposits are special cases of these residual products. These substances on the erosion surface are mechanically distributed and ultimately become segregated as mud and sand, or even iron ores. The substances which are taken out in solution may remain in solution in the sea or may be redeposited as limestone, dolomite, chert, iron carbonate, or iron silicate—in other words, as chemical sediments. Part of these substances also may be deposited as cements. The ultimate results of the destruction of the original igneous rocks, then, are the sediments, the oceanic salts, and the non-transported residual products of rock decay.

The changes above outlined involve the addition of substances of light molecular weight, such as carbon dioxide, water, and oxygen. In terms of elements oxygen is of dominant importance. The resulting minerals are on the whole of simpler molecular composition and of lower specific gravity. The actual addition of new substances has also increased volume. The unconsolidated products have a large pore space which still further increases the volume of the mass. Energy is released in an enormous amount. It has been calculated that a gram of average igneous rock releases on complete decomposition at least 120 calories of heat.

This change was called katamorphism by Van Hise. By katamorphism the rock tends to become adapted to a surface environment. The resulting product may be compared to a solution, both solid and liquid, of the original rock substances and the atmosphere and hydrosphere.

But there is ever present a reverse or anamorphic tendency which has maximum effectiveness in producing results in proportion as the substances on which it works have suffered katamorphism. Its effects are conspicuous on the sediments; they are much less conspicuous on igneous or crystalline rocks. No sooner have sediments been deposited than they tend to become consolidated by settling and by infiltration of cements. This process of induration is aided by the pressure of the accumulating sediments, and as this pressure due to burial increases, other changes take place. The substances which had been added in katamorphism are forced out: first the water, then carbon dioxide, ultimately oxygen. The bases are recombined with the alumina and silica to reproduce some of the silicates of the original rock; not all of the silicates, however, for certain of the bases have been carried to the sea where they remain in solution, and thus the original ratios of bases to alumina and silica cannot be reproduced without the addition of bases from without. The mineral molecules are on the whole more complex. Volume decreases by elimination of pore space, by elimination of substances, by new molecular groupings of higher density. A schistose or slaty structure is developed. Energy is absorbed. In proportion as the rocks are buried by the load of overlying sediments or in proportion as they suffer mechanical deformation or contact metamorphism these anamorphic changes are expedited. The changes tend in general to make the rocks approach the igneous rocks in mineral and chemical composition.

The succession of katamorphic and anamorphic changes above outlined constitutes the metamorphic cycle. It is not necessary to assume that all rocks undergo this cycle. The cycle may be changed to a reverse phase at any point, but the tendency is the same. The recurrence of cycles of the type above described constitutes great earth pulsations. The movement is in one sense oscillatory. Van Hise has used the term "zone of katamorphism" for the region near the surface where katamorphic processes are

at a maximum and the "zone of anamorphism" for a deeper region where the reverse changes are at a maximum; thus emphasizing influence of depth on metamorphic changes. These terms are extremely useful in the general sense in which Van Hise used them. It is difficult, however, to use them in the inductive study of rock changes, for so may other factors enter that at any depth the changes may be in opposite directions for different kinds of rocks or for the same rock at different times. The conception of the metamorphic cycle is better adapted to an inductive study of the rocks, for it relates merely to the succession of changes in the rock without reference to depth.

INFERENCES AS TO SIGNIFICANCE OF CYCLE

It is not enough merely to have established the existence of these cycles. We are interested in knowing the total energy changes involved, what keeps the cycle going, whether the cycle is closed, the net results in distribution of rock substances.

ENERGY CHANGES INVOLVED IN THE CYCLE

Much remains to be learned about the energy changes in common rock alterations, but enough is quantitatively known to enable us to state, with some confidence, that the changes of the metamorphic cycle result in a permanent net loss of energy from the system in the form of heat. It may be assumed from this and from a priori reasoning that it is this running down of energy which keeps the cycle going. In the igneous rocks energy is locked up in the molecular combination of minerals which under katamorphism is liberated as heat and much of it permanently lost. As this change involves expansion, it is constantly opposed by gravity, while in the anamorphic phase of the cycle gravity controls, leading to a diminution of volume. We may suppose that at any given depth some sort of energy equilibrium exists between pressure and the energy locked up in molecular combinations. So far as a rock is not adapted to this state of equilibrium, changes will go on. A granite formed under conditions of high temperature and high pressure when brought to the surface finds itself under conditions of low temperature and low pressure. The expansive

forces of the chemical reactions with the surface elements or expansive forces mechanically locked up in crystalline structure are but feebly resisted by gravity. The rock adapts itself to the new conditions of equilibrium. Unconsolidated sediments, when buried beneath the surface, reach new conditions of temperature and pressure, and readjustment is required to establish a condition of energy equilibrium. The constituents of the sediments are forced together by gravity, and energy is locked up in the molecular combinations, only to be lost again as the rock later comes under katamorphic conditions.

If heat is permanently lost by the pulsational or cyclic changes, while gravity remains constant, it may be supposed that the energy available for rock change at a given depth becomes lower. In order that the rock may fully complete its cycle by storing up energy in one phase equal to that lost in another it must go to a point deeper within the earth, where increased effect of pressure can make up for the loss of heat during the cycle. The running down of energy therefore implies the permanent accumulation of metamorphic products instead of reproducing igneous rocks on the original scale.

The probable incompleteness of the metamorphic cycle, as inferred from energy changes, is more satisfactorily indicated by field evidence to be noted below.

GEOLOGICAL EVIDENCE THAT CYCLE IS NOT CLOSED

1. *Subcrustal fusion.*—Completion of the cycle would involve reproduction of igneous rocks from sediments wherever they have reached sufficient depth—so-called subcrustal fusion. So far as observation goes, the common results of anamorphism are schists and gneisses characterized by greater abundance of platy and columnar minerals than the original igneous rocks. Locally, near igneous contacts, anamorphism reproduces rocks indistinguishable from the original igneous rocks. We do not attempt to show that subcrustal fusion has not occurred on some scale, but believe that there is no adequate evidence within our zone of observation that this has been accomplished on a large enough scale to complete the metamorphic cycle for anything but a small proportion of metamorphosed rocks. The lowest known rocks of the geological

column, the Keewatin rocks of Lake Superior, are for the most part fresh basalts with minor quantities of sediments which certainly have not been liquefied, notwithstanding the fact that they have been buried to maximum depths known to our observation. The great Laurentian batholiths of granite intruding the Keewatin and lower portions of the Huronian sediments have been regarded as the fused lower beds of the Huronian series fused by reason of depth of burial. And yet when these same Huronian sediments are followed out they are found in some adjacent areas to rest unconformably, with basal conglomerate, on an old basement of granite or Keewatin green schists with no signs of fusion. This depth has not been sufficient to cause fusion. The extreme of anamorphism shown is a schistose structure resulting from rock flowage in part of these rocks. It is known both by field and experimental observation that rock flowage producing schistosity does not require fusion. Adams[1] has shown experimentally that even to depths greater than 12 miles the weight of overlying rocks alone is not sufficient to close cavities—much less liquefy the rock. The only evidences for fusion are around the peripheries of intrusive igneous rocks. These intrusions are, on the scale of the earth, relatively insignificant masses, which have worked their way upward from a much deeper zone, carrying up energy necessary for the fusion.

In short, the metamorphic cycle within our zone of observation has usually not been completed. Since Keewatin time at least, the cycle has resulted in the gradual accumulation of sediments and their equivalent schists. Some small parts have been reconverted to igneous rocks around igneous intrusions. Whether beneath the Keewatin, sediments have been more largely converted into igneous rocks, we have no means of knowing. It may be that the span of time between the Keewatin and the present represents too small a part of the geological record from which to drawn inferences, but it is all we have as a basis of observation.

2. *Salts of the sea.*—Certain salts split off from the cycle and remain in the ocean. The salinity of the sea has been regarded as continuously increasing since the beginning of geological time.

[1] *Journal of Geology*, XX (1912), 97–118.

This cumulative extraction of salts must have an effect ultimately on the composition of the rocks of the shell, though perhaps so slight and so minutely distributed through a great mass of rocks that there is little hope of measuring it.

3. *Limestone.*—Another cumulative segregation accompanying the metamorphic cycle which has come to be recognized only recently is the segregation of lime near the earth's surface. As we follow carefully and quantitatively the anamorphic changes of all kinds of rocks, the fact stands out conspicuously that excess of lime is expelled by anamorphism. The schists and gneisses characteristic of anamorphism contain a minimum of lime carbonate or even of lime silicates. To only a very limited extent lime enters into the constitution of platy or columnar minerals adapted to the anamorphic state. This expulsion of lime in anamorphism suggests a concentration of the lime near the surface. This is further suggested by another fact. It may be easily calculated what proportion of limestone to other sediments could be expected from the breaking down of igneous and crystalline rocks of average chemical composition, and on various calculations this has been found to range from 5 to 12 per cent. It is impossible to state exactly the actual proportion of limestone to other sediments in our zone of observation, but the available facts point to a much higher percentage of limestone, anywhere from 25 to 50 per cent. It might be objected to this argument that limestones tend to become localized on continental areas with corresponding deficiency in oceanic basins, beyond our direct zone of observation. This is entirely possible but so far as facts are available from dredging, or from computations from the rate of deposition of deep-sea deposits, there does not seem to be this compensating deficiency.

4. *Dolomites.*—Dolomites seem to be more abundant in older and more highly metamorphosed geological terranes than in later ones. As the detailed changes of the metamorphic cycle are followed, we find that magnesia persists through the cycle to a much larger extent than lime, as attested by actual analyses of related series of specimens. The recurrence of cycles should lead to an increased percentage of lime over magnesia in the great carbonate formations. That limestones are in larger proportion to

dolomite in later as compared with earlier formations seems to be a pretty well-established fact. If it is true, it supports our inference of the progressive accumulation of limestone near the earth's surface.

5. *Alumina and silica the carriers.*—We are beginning to think of the cycle as one which is traveled through principally by alumina and silica; that these substances act as buckets which carry out toward the surface the bases in different relative proportions. The lime and soda are not carried back to a large extent. The potassa and magnesia are carried back to a larger extent. Iron, so far as we know, is carried pretty well through. Water and carbon dioxide in katamorphism are the effective agents in breaking up the combinations of the alumina and silica and thereby unloading the buckets. In the anamorphic phase of the cycle, the water goes down in the otherwise empty buckets in combination with alumina and silica as clay, but only for a short distance, because the hydrates are not adapted to the conditions of pressure below. Alumina and silica are not only redistributing substances, but by their combinations are the carriers and distributors of the energy involved in the changes.

CONCLUSION

In summary, then, the metamorphic cycle may be regarded as indicative of a great pulsational alteration of the earth's surface, kept going through the running down of energy and its escape from the earth, the cycle being an expression and vehicle of this running down of energy. This cycle involves reversals of processes which keep the rock materials within certain limits of mineral condition and distribution, but these reversals are not quite compensating, with the result that there is a residual accumulation and redistribution of certain substances such as sediments, schists, and gneisses, and salts of the sea. Some of the accumulations are definitely known, some are inherently probable, some are merely suspected.

If there is truth in this general conception of the net results of metamorphic cycles, the study of metamorphism may become somewhat prognostic if we use it to direct our search for some of these larger cumulative results which are now obvious in detailed work.

The discernment of these results will require a much wider range of study and quantitative observation than we have before attempted.

The acceptance of this view of the significance of the metamorphic cycle involves perhaps a slight modification of the prevalent interpretation of Hutton's great law of uniformitarianism, that the present is the key to the past. In metamorphism the same series of processes are operating today that have operated in the past, but they have slowly made over the rock types and redistributed them vertically and horizontally, with the result that while the same processes act today as have acted in the past, they are today operating, we infer, on different proportions and distributions of substances, with consequently differing emphasis and producing slightly different results.

Loewinson-Lessing, Franz. "The Fundamental Problems of Petrogenesis, or the Origin of Igneous Rocks," *Geol. Mag.*, N.S., Dec. V, VIII (1911), 248–57, 289–97.

Harker, Alfred. "Some Aspects of Modern Petrology," Vice-presidential address before Section C of the British Assoc. Adv. Sci., Portsmouth, 1911. Pp. 12.

Iddings, Joseph P. "Problems in Petrology," *Proc. Amer. Phil. Soc.*, L (1911), 286–300.

Cross, Whitman. "The Natural Classification of Igneous Rocks," *Quar. Jour. Geol. Soc.* (of London), LXVI (1910), 470–506.

Discussion of the great problems of igneous rocks is a necessary forerunner of any unanimity of belief concerning them, such as must exist before the science of petrology can claim to have advanced beyond the formulative stages. In the papers here under review many of these problems are freely discussed from different standpoints. An outline of their scope and character may serve to show the present condition of the science of petrology.

The problems of petrogenesis discussed by Loewinson-Lessing are indeed fundamental, some of them reaching so far back into the earth's history or dealing with phenomena of such depths in its mass that few petrologists speak with confidence of their solution upon our present meager basis of established fact. The author of the essay under review is one of those who do speak with an assurance for which there is scant justification in the considerations presented, or, indeed, in the knowledge of today. Yet such discussions are of undoubted interest and value in more ways than one.

Loewinson-Lessing believes in two primordial magmas which he calls granitic and gabbroidal. He advocates, as he acknowledges, the ideas of Bunsen and Michel-Lévy in modified form. It is sought to establish the primordial nature of these two magmas by discussing the average composition of the earth's crust. The known variations exhibited by igneous rocks are ascribed to differentiation, assimilation, and, in apparently subordinate degree, to mixture of the two original magmas.

In discussion of "the average chemical composition of the earth's

crust and the primordial magma" Loewinson-Lessing criticizes the results reached by Clarke and Washington and others as obtained by incorrect methods, but accepts their averages as accidentally nearly correct since they agree well with the mean of certain average compositions for granite and gabbro obtained by Daly. These latter averages seem to be accepted by Loewinson-Lessing as representing his primordial magmas in preference to any figures of his own, but they too must have been obtained by the methods esteemed faulty, and when one considers the different analyses various men would use in securing averages of "granite" or "gabbro," or any other rock type or group, one almost wonders where the value of such compilations comes in. If the author's conception of granite or gabbro is as peculiar as that announced for "syenite" one may well look askance at averages of his compilation. He says the mean of Daly's granite and gabbro "corresponds almost exactly to the syenitic magma." This mean carries 4.40 per cent MgO and 6.66 per cent CaO. A rock of this composition falls in subrange tonalose (II.4.3.4) and its norm contains 24.2 per cent anorthite and 11.9 per cent of quartz!

It is clear to Loewinson-Lessing that this "syenitic" mean represents two primordial magmas rather than one. This thesis is supported chiefly by dogmatic assertion. There is not much to convince the reader, for example, in his assertion that the "syenitic" magma could not be the original one "because the syenite is itself a derived magma." Nor is it any more conclusive that the primitive monzonitic and essexitic magmas of Rosenbusch cannot be so regarded "because the monzonites are one of the products of the largely differentiated gabbro-syenitic magmas, but are not sensibly subject to differentiation." Rosenbusch apparently does not know this and possibly he may question the statement!

By equally cogent reasoning Loewinson-Lessing disposes of all other views as to primordial magmas and reaches four generalizations which may be concisely stated as follows: (1) There were two primordial earth magmas, of granitic and gabbroidal composition. (2) "The different members of the granite formation and the gabbro-pyroxenitic-peridotitic formation occur in much larger bodies and have a far greater development than other eruptives," which is considered evidence of their primitive character. (3) The primordial nature of granitic and gabbroidal magmas is shown by abundance of facies and of associated differentiation products, which cannot be equally prominent with the intermediate magmas because they are themselves differentiation products. (4) "The original independence of the granitic and the gabbro-noritic formations" is indicated

by the absence of such transitional types as would speak for the production of one from the other through differentiation.

The second problem of petrogenesis discussed is "the causes of the diversity of igneous rocks." The processes invoked are differentiation and assimilation. The author does not seem to realize that we are just beginning to acquire the data needed for an understanding of the actual chemical and physical processes involved in what he discusses so confidently. Eutectic magmas are spoken of as though well known. The process by which a non-eutectic magma may separate into its eutectic and various parts representing the dissolved substances is not considered. No creative suggestions like those characterizing Vogt's writings are found in this paper.

That assimilation of foreign matter has disturbed the natural course of differentiation to a great extent is Loewinson-Lessing's main contention. He cites a list of advocates of assimilation, but the main argument for it is contained in the question raised, "Is not assimilation a phenomenon that must be expected a priori in intrusive bodies, for it is difficult to imagine a magmatic basin heating the rocky masses in contact with it for a long period without partly dissolving them?" It is indeed necessary to recognize that where conditions of fusion exist that form of solution will take place, and further that where such conditions do not exist the fusion will not occur. Conditions we do not yet understand set limits for this process, not the range of a petrologist's imagination.

That many magmas represented in rocks open to investigation came from depths where the conditions of fusion and assimilation existed is seemingly incontestable. For magmas or rocks of such origin the course of differentiation producing them may have been decidedly interrupted and one can readily conceive of various plausible conditions greatly complicating the genetic problem. In this very situation lies the basis of the view, held by the present writer, that petrogenetic classification for all rocks must remain impracticable.

But the assumption that assimilation has taken place generally in large intrusive bodies at contacts now visible is not plain to many petrologists. Loewinson-Lessing's simple statement that "In an intrusive body of laccolithic type assimilation takes place in the manner of stoping as elucidated by Daly" illustrates the ease with which he accepts generalizations favorable to his theories. The origin of nepheline syenite from granitic magmas through the reactions connected with assimilation of limestone, as hypothecated by Daly, is also accepted by Loewinson-Lessing as assisting him out of a recognized dilemma.

"What origin have the igneous rocks and why are they represented by the same types in all periods?" is the third question discussed. Loewinson-Lessing believes in a fluid nucleus, that no trace of the primordial crust remains, that all magmas of rocks were derived by the fusion and refusion of the crust, principally from its lower surface. As the materials are always the same worked over and over again, the range of composition cannot change except that probably extreme products will become more abundant with time. Theory and speculation run persistently all through this discussion unbridled by too close connection with fact or formulated laws. The following quotation (p. 254) seems to indicate the author's point of view: "We take it as a *fact* that there must be admitted two independent primordial magmas, while all other eruptive rocks are derivates from them, originating by assimilation and differentiation. Such a *hypothesis* is based on the following facts and considerations." The italics, inserted by the reviewer, serve to illustrate the lack of distinction between fact, theory, hypothesis, and opinion prevailing in the discussion and markedly decreasing its value.

It is worthy of comment that Loewinson-Lessing does not go to the root of the matter by considering the origin of the "primordial" magmas assumed by him and their relation to the earth as a whole. Nor does he touch the great problems to which Harker gives his attention.

The special theme of Harker's address is "the geographical aspect of petrology," introduced by a review of the geographical distribution of igneous rocks. Then comes a discussion of "the alkaline and calcic branches" and of "the relation between tectonic and petrographical facies." The latter is illustrated by references to the relations existing in the north British Tertiary province, as worked out by Harker. The bearing of the considerations presented on petrogenesis and systematic petrography is taken up briefly in conclusion.

The aim in Harker's address, as in his valuable and interesting work on the *Natural History of Igneous Rocks*, is plainly to contribute to a logical interpretation of the known facts and relations of igneous rocks. This should be the ambition of every petrologist, yet in the succeeding comments on this address the reviewer's wish is to give point to his own belief, in which he is not alone, that some of the great generalizations accepted by Harker, and many with him, are not yet sufficiently in accord with the facts to serve the uses made of them. In the desire to elucidate, what is in its essence most complex and elusive, the experience of the ages with premature or hastily formulated hypotheses must not be forgotten.

As T. W. Richards has anew and most felicitously stated the principle which should guide us as petrologists, "The soundness of all important conclusions of mankind depends on the definiteness of the data on which they are based. . . . . The more subtle and complicated the conclusions to be drawn, the more exactly quantitative must be the knowledge of the facts."[1]

It may be well to anticipate somewhat by noting that the generalizations particularly questioned by the present writer are the existence of the alkaline and calcic branches of igneous rocks and the correctness of various forms of statement concerning their distribution on the earth, their genetic and tectonic relations. The first-named and most popular conception rests almost wholly on the strongly marked and contrasting characters of certain very different series or families of rocks. It has never been justified by thorough and unbiased study of the host of intermediate series.

In the discussion of geographic distribution Harker first refers to the commonly accepted generalization of petrographic provinces. Few, if any, petrologists question the fact of the petrographic province. But few provinces have thus far been so thoroughly investigated that we know the full range of rocks occurring in them, their composition, and occurrence. The best known provinces are ones of strongly marked characters, as a rule.

The main theme of the address is, however, not the limited problem of the petrographic province but rather that of the two great hypothetical branches of igneous rocks variously called Atlantic and Pacific, alkali and subalkali, alkalic and calcic, etc. In the "Natural History of Igneous Rocks" Harker used the first named terms but here substitutes "alkaline and calcic." This division is referred to as "now becoming recognized as the most fundamental distinction to be made among igneous rocks" and our author's principal topic is, in fact, the broad relationship of these branches to the nature of tectonic movements in the earth's crust and the genetic significance of this relationship.

Such an address is not the place for details of fact, yet the layman and general geologist listening to this discussion must have been misled by the positive form of several generalizations made by Harker. Some of these are qualified, it is true, but so grudgingly and inadequately as to minimize the effect.

While no one has yet attempted a thorough and fair definition of the alkaline and calcic branches, Harker refers to their characters as "too

[1] Faraday lecture, *Science*, XXXIV (1911), 538.

well known to need recapitulation." The arbitrariness of referring a host of rocks of intermediate composition to one or the other of these undefined classes is not acknowledged. Exceptions are called "anomalies" and treated as of no moment. It is said that "A given province is either of calcic or of alkaline facies, typical members of the two branches not being found together." This may be true if a province is not a province when it has mixed characters. Again, it is said that "it is possible to map out the active parts of the earth's crust into great continuous regions of alkaline rocks on the one hand and of calcic rocks on the other." That may be true if numerous "anomalies" are disregarded and given a free hand in mapping through absence of criteria really distinguishing the branches.

The interesting generalization most dwelt upon by Harker is expressed in these words, "The distribution of different kinds of rocks is seen to stand in unmistakable relation to the leading tectonic features of the globe." As here stated most petrologists of experience may agree with the author, for he merely says "different kinds of rocks" and does not specify the relation. In truth all the essential elements of this relation are still to be determined by careful study of many districts. When Harker jumps to the further conclusion that the significant relation is between the two branches of magmas and the different kinds of stresses producing folding or faulting of the crust, he goes far into the realm of hypothesis. That his devotion to this hypothesis leads him into apparently forced interpretation of admitted facts seems abundantly illustrated by his own sketch of the relations of the alkaline and calcic branches in the north British Tertiary province.

In this area of various epochs of eruption Harker is confronted with the necessity of explaining a provincial mingling of alkaline and calcic rocks. This is accomplished to his own satisfaction by postulating changes in the fundamental character of underlying magmas in harmony with the tectonic history, faulting having predominated in certain epochs in which alkaline rocks are thought to play the active rôle, while folding at other times is accompanied by the appearance of the calcic lavas.

The difficulties of this situation are numerous in any case. Basalts of puzzling associations are placed in the alkaline branch because of sodic zeolites which are thankfully recognized as really primary and a most important part of the magma, since through them the alkaline nature of the basalts can be determined. (This idea, if correct, may be conveniently applied to determine the primary or secondary origin of alkalic zeolites. In a basalt of a calcic series of lavas such zeolites are

necessarily to be regarded as formed by solutions bringing soda from a foreign source.)

Harker finds some rhyolites "without very distinctive characters" but the association with trachytes settles, for him, the question of their reference to the alkaline branch. This doubt must have been caused by lime, which is an "anomaly" in an alkaline rhyolite. Certain widespread basic sills "have little that is indicative of alkaline affinities," but they are associated with some porphyritic dolerites of more sodic character, and these are elsewhere associated with more "typical alkaline rocks," so the akaline nature of the first mentioned sills is considered established. Harker does not seem to realize that his argument also connects "typical alkaline rocks" with others of calcic character in a manner to illustrate the fact of transition from alkaline to calcic magmas.

He refers to "augite-andesites which taken by themselves must be assigned to the calcic division" but these "aberrant types" are regarded as products of a "subsidiary differentiation" which is apparently able to transgress the laws of ordinary differentiation.

The cases just cited, and others like them, seem to justify the suspicion that perhaps the north British Tertiary province illustrates the existence of intermediate parent magmas whose derivates through differentiation naturally tend in one direction to exhibit alkaline affinities or even "typical" characters, and in the other the more calcic varieties. Why is this not a natural result from differentiation of intermediate magmas?

The closing section of Harker's address, on "Petrogenesis and Systematic Petrography" is a plea for a genetic classification of igneous rocks. As in such arguments generally the necessity for many classifications of these objects of tremendously complex relations and history is ignored. The essential difference of the one systematic classification upon which our nomenclature must rest, *the* system of petrography, from other classifications of petrology is also ignored. The best illustration of this limited view of the situation is given by Harker's reference to the present writer's remark that "only generalizations without known exceptions in experience can be applied to the construction of a system that may be called natural," to which Harker seems to think his own attitude is antagonistic, namely, "I hold, on the contrary, that such a science as geology can be advanced only by the inductive method, which implies provisional hypotheses and successive approximations to the truth." The first opinion was expressed with regard to petrographic system only. The chief desideratum in a stable, non-theoretical, petrographic system is not the facility of naming a rock (important as

this is) but the freedom such a condition would give to the broader and often conflicting generalizations of petrologists and geologists concerning the various deep-lying relations of igneous and other rocks. Picture the future of *systematic petrography* if based on "provisional hypotheses" and "successive approximations to the truth"!

The critical reader of this address cannot fail to be impressed at the opening and again at the close of the discussion by an inconsequence in the use of the terms petrology and petrography which has its counterpart in other places and leads to doubt as to the logic of the reasoning in certain important particulars. The distinction between petrology as the broad philosophical science of rocks, and petrography, as the descriptive or systematic part of petrology, is well-nigh universal today. This usage is both approved and violated by Harker. In his introductory remarks he acknowledges that the idea as to the limitations of *petrography* "correctly denotes its purely descriptive nature" and yet asserts that "*petrology* is at the present time in a state of transition . . . . from a merely descriptive to an inductive science. . . . ." Has the work of Bunsen, Durocher, Rosenbusch, and Brögger—not to mention many others—been "merely descriptive"?

Again, in his summary, Harker deplores the attitude of those who would abandon efforts to place *petrography* upon a genetic basis, which would be to renounce its claims as "a rational science," while he, in contrast, takes "a more hopeful view of the future of *petrology*"! There are many petrologists who hold the former view and yet join enthusiastically with Harker in the latter outlook, having regard for the distinction which he at times seems to lose sight of.

The discussion of the "Problems in Petrology" by Iddings is different from those of Harker and Loewinson-Lessing in that it is a statement of the problems of today, the ones which present knowledge makes most profitable for the labors of petrographer and petrologist, rather than of the ultimate questions, or even those dependent on provisional generalizations. It is the problems of the rocks themselves and those to be formulated from the closer study of petrographical provinces which Iddings specially considers, though the results are of interest also through their bearing on still more remote and fundamental relations.

The "actual mineral composition of igneous rocks" is first taken up as "a great field of research, imperfectly cultivated, capable of yielding immediate returns of the first importance for the solution of other problems connected with the mineral composition of these rocks." The

study of texture is urged, as it "is a very definite exponent of physical conditions that attended the crystallization of each igneous magma." The accurate determination of the minerals of rocks as to quantity and composition is declared essential to a comprehension of the problems of igneous rock formation which are specified. The relation of mineral to chemical composition and conditions of crystallization is given as one of the pressing questions, with two particular phases: (1) the apparent absence of molecules called *occult* which the bulk analysis would indicate must be present in certain rocks; (2) the various modes possible in magmas of the same composition. The occult molecules are those held by recognized minerals in solid solution. Notable illustrations of these conditions are given and the difficulty of correlating rocks solely on mineral composition is pointed out.

It is shown that the elucidation of the laws controlling the production of mineral compounds from molten magmas is a problem for joint attack by petrographer, chemist, and geophysicist.

Under the heading "The Mathematics of the Petrology of Igneous Rocks" Iddings develops the view that magmas and the mineral aggregates resulting from their crystallization must be interpreted in terms of stoichiometric chemistry and quantitative physics: that igneous rocks constitute a series which is unbroken in itself; and that the division of such a series into parts for systematic or descriptive purposes is naturally, because inevitably, by some arbitrary choice of units. The rock "type" is declared to be "subjective, inherent in the petrographer, not the rock."

The abstract quantitative or mathematic relations of the basic properties of igneous rocks are dwelt upon to show a fundamental difference between them and organisms. Iddings deprecates, therefore, the form given the idea of Harker that we may come to a genetic or natural classification of igneous rocks based on some "fundamental principle analogous with that of descent, which lies at the root of classification in the organic world." The terms "consanguinity," "parent magma," "family," and others are expressive but should not lead to biological analogies, for we are dealing, not with organisms, capable of reproduction, but with "a series of chemical solutions and their solidified phases," although they "may be related to one another by reason of differential diffusion or fractional crystallization.

Other problems of igneous rocks are discussed by Iddings under the head of "Petrographical Provinces." Although himself one of the first to recognize and support the generalization outlined by Judd he acknowl-

edges that as yet "little or no attempt has been made to define more precisely what constitutes the characteristics of any so-called petrographical province." "Nothing approaching completeness of definition, either as to composition of the rocks, or extent and limit of the region of occurrence, has ever been attempted." Iddings does not believe that the major provinces or regions of the earth, thought by Becke, Harker, and others to be characterized by the "Atlantic and Pacific" or the "alkaline and calcic" branches, are entitled to recognition.

From Iddings' standpoint the problem before petrologists today, respecting geographic distribution, "is the investigation and exact definition of the districts and regions of igneous rocks in all parts of the world, with the purpose of obtaining the data with which to form definite conceptions of what have been termed petrographical provinces." Existing data make it clear to him "that there are many kinds of such groups of igneous eruptions and not two strongly contrasted series; that they blend into one another in composition; that the delineation of the regions, or provinces, may be pronounced in some instances and ill-defined in others."

In view of Iddings' opinion concerning the very incomplete data of igneous rocks themselves, their relations and distribution, it is natural to find him expressing the belief that major problems such as "the relation of the composition of igneous rocks of different parts of the earth to its isostacy"; "the relation between the kinds of magma erupted in a particular region and the dynamical events within the region"; and the question of original homogeneity or heterogeneity in the earth, must wait for their reasonable solution on the accumulation of a great amount of exact data, by petrographer, chemist, geophysicist, and geologist.

The article by the present writer on "the natural classification of igneous rocks," which antedates the other discussions here reviewed may be briefly referred to. In the first place, petrographers and petrologists are reminded that a classification of rocks may be called *natural* only when the factors used in its construction are really the facts or relations of nature. It is pointed out that the generalizations used in many attempted classifications were so erroneous or inaccurate as to make the result peculiarly unnatural. The special object of the discussion is a defense of the quantitative classification of igneous rocks from the criticism urged most forcibly by the advocates of natural classification that the quantitative method is unnatural and arbitrary.

The authors of the quantitative system were moved to its formulation

by the belief that genetic relations and some of the characters of igneous rocks are not adapted to serve as bases of their systematic petrographic classification, i.e., the one system on which their scientific nomenclature rests. In this paper the availability of various factors is given renewed discussion. Under the heading "Factors of Chemical Composition," objection is made to the primary distinction of Atlantic and Pacific Kindred or the alkaline and calcic branches as inaccurate and vague. It is pointed out that if the differences of composition are partly due, respectively, to primeval variation, magmatic differentiation, and assimilation, three independent causes, the laws of differentiation alone cannot be applied to all rocks in a systematic way.

In considering the propositions emanating from Rosenbusch to use these laws in formulating the current system the distinction of two great magmatic series and the division of "dike rocks" are characterized as really unnatural. Instances of "dike rock" association and occurrence conflicting with the basal generalization are given.

Classification by eutectics is reviewed, with reference to the propositions of Becker and Vogt, and rejected, as inapplicable to all rocks, and based on a part of the rock at best. It is furthermore extremely hypothetical at the present time.

Factors of mineral and textural characters are next considered and the well-known fundamental objections to their systematic use are reviewed. The former is not only too complex for practical use but we now know that it is not, as once assumed, a simple function of chemical composition, but depends partly on variable and independent physical conditions.

The section of this paper dealing with the quantitative system is devoted to correcting certain misconceptions, to explaining that the norm is largely a means of expressing the molecules actually in magmatic solution and not a pure figment of the imagination, and to reviewing certain criticisms, particularly some expressed by Harker.

WHITMAN CROSS

Reviews

The Fauna of the Moorefield Shale of Arkansas. By GEORGE H. GIRTY. U.S. Geol. Survey Bull. 439. 1911. Pp. 148; pls. 15.

In 1895 Professor H. S. Williams[1] called attention to the recurrence of certain Devonian types of fossils in beds of Mississippian age in Arkansas, the formation containing these recurrent species being that which has since come to be called the Moorefield shale. At still an earlier date McChesney[2] described several species from this formation near Batesville, Arkansas, referring them to the age of the Hamilton group of New York, because of the manifest similarity between these species and certain Hamilton forms. Because of this unexpected reappearance of Devonian genera of invertebrate fossils in the Moorefield shale, this fauna is of especial interest to students of Mississippian paleontology, and the full discussion of the fauna, with descriptions and illustrations of all the species, is a welcome contribution to our literature.

The stratigraphic position of the Moorefield shale is between the Boone chert below and the Batesville sandstone above, it being separated from the subjacent formation by an unconformity. The complexion of the fauna is quite different from that of any of the formations of the standard Mississippian section of the Mississippi Valley, and consequently the correlation of Moorefield shale is not a perfectly simple matter. Dr. Girty has followed the usual custom of those who have given some study to the fauna, in considering it to represent a time about equivalent to the St. Louis limestone of the standard section. One of the most interesting features of the fauna is its relationship to the early Carboniferous faunas of Nevada, a relationship first pointed out by Williams. The forms which most clearly suggest this relationship are *Liorhynchus carboniferum*, *Productella hirsutiformis*, and *Moorefieldella eurekensis*. Another fauna with which that of the Moorefield shale is compared by Dr. Girty, is the fauna of the Caney shale of Oklahoma, a formation whose age is subject to a wide difference of opinion: Dr. Girty is of the opinion that it is Mississippian in age, while others believe it to be of Pennsylvanian age on account of the presence of certain plant

[1] *Am. Jour. Sci.*, 3d ser., XL, 94–101.

[2] *Descriptions of New Species of Paleozoic Fossils* (1860).

remains of apparent Pottsville age in beds subjacent to the Caney shale. The final correlation of the Mississippian faunas of northwestern Arkansas and Oklahoma must rest until much more investigation upon them has been completed.

S. W.

The Early Paleozoic Bryozoa of the Baltic Provinces. By RAY S. BASSLER. U.S. National Museum Bulletin 77.

In this paper the stratigraphy of the Ordovician and the lower part of the Silurian rocks of the Baltic provinces is considered briefly and the bryozoan fauna is described and figured. Complete faunal lists of the formations are also given.

The Paleozoic rocks of this region have usually been considered as representing a complete section of the Cambrian, Ordovician, and Silurian systems, with the exception of the Middle Cambrian. The bryozoan faunas indicate, however, that instead of the whole of the Ordovician being present only the Beekmantown (Canadian of Ulrich), the Black River (of Ulrich), and the earliest Trenton are represented. The Lyckholm and Bornholm beds, which have been hitherto correlated with the Utica, are believed to be of Richmond age and are placed at the base of the Silurian.

For the purpose of comparison, the stratigraphy of the Upper Mississippi Valley region is reviewed and the bryozoan faunas of these formations are considered briefly. Reference is made to the strata and faunas of the same age in Arctic America. From the comparison of the faunas, it is decided that the faunas of the Ordovician and the early Silurian of the Baltic provinces and of central and northern America were derived from the Arctic region. The resemblance between the faunal elements requiring shore-line conditions for migration is strong but not nearly so marked as in the types not dependent on these conditions. The resemblance is especially marked in the case of the bryozoa, for out of the 237 species found in the Ordovician and Richmond beds of the Baltic region, 86, or over one-third, are also known from America, and many others are closely allied forms.

The greater portion of the bulletin is taken up with the description of some 200 species of bryozoa. The figures for each species are inserted in the text, and this should prove a great advantage over the usual method of separating the description and the figures. The figures, although printed on rather soft paper, are, with few exceptions, very clear, and there should be no trouble in using them for identification.

Fourteen plates are made up of copies of Dybowski's original figures of many of the species, of figures showing the surface features of several species which were not well illustrated when originally published, and of figures showing the nature of occurrence and the association of the bryozoa in the rocks.

In view of the large number of species common to the Baltic and the central and northern American regions, the paper is an important contribution to the literature of the American as well as to that of the European bryozoa.

L. C. S.

Advance Chapters from Mineral Resources for the Calendar Year 1910: Mica, Graphite, Fuller's Earth, Quartz and Feldspar. Washington, U.S. Geol. Survey.

Mica, by DOUGLAS B. STERRETT: After introductory paragraphs on the micas of commercial importance and their occurrence and uses, the statistics for production are given, North Carolina, South Dakota, New Hampshire, Colorado, South Carolina, New Mexico, and Massachusetts contributed to the total. The value of production of both sheet and scrap increased over that for 1909, in spite of a slight drop in tonnage of the latter.

Graphite, by EDSON S. BASTIN: The United States produced a little less than 10 per cent of the world's production in 1910, New York and Pennsylvania giving more than half the total value. The year's production, totaling $377,176, exceeded all previous years in value. Artificial graphite was produced amounting to nearly $1,000,000 in value, and imports amounted to $1,872,592. Production by states is discussed and a paragraph on treatment of the raw material is added.

Fuller's Earth, by JEFFERSON MIDDLETON: A slight drop in tonnage and in average price per ton caused a noticeable decrease in the output for 1910. Florida produced more than all other states combined at a price slightly above the average for the United States. The total value of the product for the year was $293,709, more than twice the value of imported material.

Quartz and Feldspar, by EDSON S. BASTIN: Introductory paragraphs discuss kinds of material, methods of grinding, and uses. The production of quartz showed a drop of 53 per cent in tonnage and 22 per cent in value, as compared with 1909. The decrease was due to diminished production of quartz for flux in copper smelting and the shutting down

of a mine and mill at Roxbury Falls, Conn. Feldspar showed an increase of about 20 per cent in value of product, the total reaching half a million dollars for the first time. Maine produced more than one-third of the total value, with only a little more than one-fourth of the total tonnage. The value of the year's production of feldspar and quartz amounted to less than three quarters of a million dollars.

A. D. B.

Denudation and Erosion in the Southern Appalachian Region and the Monongahela Basin. By LEONIDAS CHALMERS GLENN. U.S. Geol. Survey. Professional Paper 72. 1911. Pp. 137; fig. 1; pls. 21.

This report presents a summary of the results of an examination made for the purpose of studying the effect of deforestation and consequent erosion of the steep mountain slopes on geologic, hydrologic, and economic conditions, both in the mountain region itself and in the surrounding area through which the streams flow. The area under consideration contains the largest and most valuable hardwood area in the United States.

The removal of forests by unscientific lumbering, by forest fires, for mining, and for agricultural purposes leaves the slopes in a condition to be eroded easily, making the run-off of rains greater and more sudden, causing floods that do great damage in the valleys. The remedies suggested are: (1) putting the cleared slopes into grass or terracing them, (2) preventing the clearing of steep slopes, and (3) the prevention of forest fires that usually follow in the wake of lumbermen.

The existing conditions are described for each river basin, and special consideration is given to the large floods of recent years. At the end in tabular form, the various river basins are classified according as their streams are in (1) timbered basins where little damage is done by floods; (2) cleared basins where floods do much damage; (3) cleared basins where floods do little damage because the soil is porous or else the clearings are largely in grass; and (4) timbered areas in which the tributaries have damaging floods due to logging on steep slopes. A. E. F.

Characteristics of Existing Glaciers. By WILLIAM HERBERT HOBBS. New York, 1911. Pp. xxiv+301; figs. 140; pls. 34.

In this work emphasis is laid on the great difference in the laws governing mountain glaciers and bodies of inland ice, and on the geological effects of the two classes of glaciers. The dissimilarity in the

sculpturing by mountain glaciers at high and at low levels is clearly brought out. The recession of cirques is the principal process at high levels, while at low altitudes the deepening of valleys and characteristic deposits are the resulting features. A distinction is drawn between high altitude and high-latitude sculpturing. The glaciers in the former location are located on high mountains and therefore have steep gradients which is not necessarily the case for high-latitude glaciers.

In the large polar areas where inland ice is the characteristic form of glaciers, the Arctic and Antarctic each have their own characteristics, which are widely different. The north polar region is largely a sea indented on its margins by projecting land masses, while the south polar region is a continent surrounded by ocean. In the Arctic region the ice is less in areal extent than the land on which it rests, and the bergs derived from the glaciers are relatively small in size because they are calved in narrow fiords, and they are composed of solid glacier ice.

The contrast to these characteristics is found in the Antarctic region where the ice extends beyond the margins of the land into the sea, where, with augmentation by snow, there is formed the extensive shelf ice of which the Great Ross Barrier is an example. Because of the accumulation of snow on this shelf ice the surface is very level, and its upper part is, therefore, composed of soft ice. Any solid or glacier ice present is below the water level. The bergs from this extensive shelf ice are characterized by their immense size, their rectangular shape, and their white porous ice.

All the evidence for the alimentation of the extensive fields of inland ice seems to show that augmentation of material is largely along the margins; not that the snow falls there, but that the constant winds radiating outward from the interior carry in a large measure all the snows with them, and it does not become lodged until the margin is reached.

The volume is attractive for its large number of illustrations, and to the student of glaciers, for its comprehensive list of references, which, unfortunately, are grouped at the end of each chapter, necessitating the awkward suspense of turning pages to find them. A. E. F.

The Road Materials of Washington. By HENRY LANDES, assisted by OLAF STROMME and CLYDE GRAINGER. Wash. Geol. Survey Bull. 2. Olympia, 1911. Pp. 204; figs. 51; pls. 17.

In a survey of the state for road materials, the accessibility to transportation, quantity, quality, and local demand were the principal factors

considered. One hundred and seventy-one samples were collected, and the results of the tests applied in the government laboratories are given. The best materials in each county are described, and the many figures and plates are maps indicating the places where good material is found and where the samples were collected. Practically all the samples tested were of igneous rocks, mainly basalts, and it is upon these that the state will largely rely for its road material.

A. E. F.

Geology and Ore Deposits of the Blewett Mining District. By CHARLES E. WEAVER. Wash. Geol. Survey Bull. 6. 1911. Pp. 104; fig. 1; pls. 10.

This small gold camp lies in central Washington. The region is one of a few Carboniferous (?) and Tertiary sedimentary formations that are dislocated and metamorphosed by several large igneous intrusions. Gold-bearing fissure veins cut a peridotite mass that shows considerable differentiation, and which is now largely altered to serpentine. The gangue minerals are principally quartz and calcite with which are associated pyrite, arsenopyrite, and native gold. Considerable talc is found in the vein walls. It is supposed that the mineralization was related to the intrusion of granodiorite, and it is possible that the serpentinization of the peridotite took place at the same time. The earlier workings were in the oxidized zone, and the ores were free milling, but since the sulphide zone has been reached most of the ores are treated by the cyanide process. The district was first exploited because of its placer deposits.

A. E. F.

Geology of the Berners Bay Region, Alaska. By ADOLPH KNOPF. U.S. Geol. Survey Bull. 446. 1911. Pp. 55; figs. 4; maps 2.

The Berners Bay region forms the northwestern extremity of the long zone of auriferous mineralization known as the Juneau gold belt. The rocks consists of sedimentary slates and graywackes of Jurassic or Lower Cretaceous age, metabasalts, quartz diorite-gneiss, diorite, hornblendite, and felsitic or rhyolitic dikes and sills.

The important ore bodies are largely in the diorite, and are in the form of fissure veins, stockworks, and stringer lodes. The gold occurs in the native state, associated with quartz and pyrite, and lesser amounts of other sulphides and gangue minerals, the resulting ores being usually of a low grade. Descriptions of all the mines are given.

A. E. F.

Geology and Mineral Resources of the St. Louis Quadrangle, Missouri-Illinois. By N. M. FENNEMAN. U.S. Geol. Survey Bull. 438. 1911. Pp. 73; fig. 1; pls. 6.

This region is one of Mississippian and Pennsylvanian formations, overlain by Lafayette gravels, Pleistocene glacial tills and loess, and recent alluvium. In the drilling of deep wells, the logs of which are given, Ordovician and Cambrian formations are shown to be present beneath the Mississippian strata. The Paleozoic formations have a slight dip toward the northeast.

Of economic importance are the Cheltenham fire clays, shales, and brick clays. One large Portland cement plant is in operation. The No. 6 coal of the Illinois reports has its western limit on the Illinois side of this quadrangle and is there mined.

A. E. F.

"A Revision of Several Genera of Gymnospermous Plants from the Potomac Group in Maryland and Virginia." By EDWARD W. BERRY. *Proc. U.S. Nat. Mus.*, XL (1911), 289–318.

This revision is a simplification, combining many previously segregated forms. The genera considered are: *Sphenolepis*, *Arthrotaxopsis*, *Cephalotaxopsis*, *Widdringtonites*, *Brachyphyllum*, *Sequoia*, *Abietites*, and *Pinus*.

A. E. F.

Glacial Erosion in the San Juan Mountains, Colorado. By THOMAS CRAMER HOPKINS. *Proc. Wyo. Hist. and Geol. Soc.*, XI, pp. 14; pls. 8.

In this well-illustrated paper evidence is cited against the idea, held by some geologists, that the theory of ice erosion is a fallacy.

A. E. F.

—American Institute of Mining Engineers, Transactions of the. Vol. XLI. Containing the Papers and Discussions of 1910. [New York, 1911.]

—ANDREWS, E. C. An Excursion to the Yosemite (California), or Studies in the Formation of Alpine Cirques, "Steps," and Valley "Treads." [Reprinted from Journal and Proceedings of the Royal Society of New South Wales, Vol. XLIV. Sydney, 1910.]

—ARNOLD, R. The Tertiary and Quaternary Pectens of California. [U.S. Geological Survey Professional Paper 47. Washington, 1906.]

—ATWOOD, W. W. Geology and Mineral Resources of Parts of the Alaska Peninsula. [U.S. Geological Survey Bulletin 467. Washington, 1911.]

—BARROWS, H. K., COVERT, C. C., AND BOLSTER, R. H. Surface Water Supply of the United States, 1909. Part I. North Atlantic Coast. [U.S. Geological Survey Water-Supply Paper 261. Washington, 1911.]

—BASSLER, R. S. The Waverlyan Period of Tennessee. [No. 1851, from the Proceedings of the United States National Museum. Vol. XLI, pp. 209–24. June 24, 1911. Washington: Government Printing Office.]

—BELL, J. M. A Geographical Report on the Franz Josef Glacier. With Topographical Maps and Data by R. P. Greville, and Botanical Notes by L. Cockayne. [Department of Mines, New Zealand Geological Survey. Wellington, 1910.]

—BERRY, E. W. A Revision of Several Genera of Gymnospermous Plants from the Potomac Group in Maryland and Virginia. [No. 1821, from the Proceedings of the United States National Museum, Vol. XL, pp. 289–318. Washington, 1911.]

—BONSTEEL, J. A. The Portsmouth Sandy Loam. [U.S. Department of Agriculture, Bureau of Soils Circular 24. Washington, 1911.]

—BOWMAN, ISAIAH. Well-Drilling Methods [U.S. Geological Survey Water-Supply Paper 257. Washington, 1911.]

—BROOKS, A. H. Alaska Coal and Its Utilization. [U.S. Geological Survey, Bulletin 442-J. Washington, 1911.]

—BRÜCKNER, DR. ED., ET MURET, E. Les variations périodiques des glaciers. XVme rapport, 1909. [Extrait des Annales de glaciologie t. V. janvier 1911, p. 177–202. Berlin, Borntraeger Frères, 1911.]

—BUEHLER, H. A. Biennial Report of the State Geologist, Transmitted by the Board of Managers of the Bureau of Geology and Mines to the Forty-Sixth General Assembly. [Missouri Bureau of Geology and Mines. Jefferson City, 1911.]

—BURNS, W. G. Illinois Section of the Climatological Service of the Weather Bureau. [Annual Summary, 1910. U.S. Department of Agriculture. Nashville, Tenn., April 25, 1911.]

—Butts, C., Dale, T. N., Richardson, G. B., Shaw, E. W., Deussen, A., and Burchard, E. F. Advance Chapter from Contributions to Economic Geology (Short Papers and Preliminary Reports), 1910. Part I, Metals and Non-Metals Except Fuels. Structural Materials. [U. S. Geological Survey Bulletin 470-G. Washington, 1911.]

—Cameron, F. K. The Soil Solution, the Nutrient Medium for Plant Growth. [Easton, Pa., Chemical Publishing Co., 1911.]

—Carneiro, B. P., and De Sousa, Jose Ayres. Memorias e Projectos de Açudes. Commissão do Açuide de Quixadá. Commissão de Açudes e Irrigação. [Ministerio da Viacão e Obras Publicas. Inspectoria de Obras Contra As Seccas. Publicação n. 8. Serie II, H—Memorias de açudagem. Rio de Janeiro, 1910.]

—Cirkel, Fritz. Chrysotile-Asbestos. Its Occurrence, Exploitation, Milling, and Uses. [No. 69, Canada Department of Mines. Ottawa, 1910.]

—Clark, A. H. The Systematic Position of the Crinoid Genus Marsupites. [No. 1845, from the Proceedings of the United States National Museum, Vol. XL, pp. 649–54. June 24, 1911. Washington: Government Printing Office.]

—Clark, H. H., Roberts, W. D., Ilsley, L. C., and Randolph, H. F. Electrical Accidents in Mines: Their Causes and Prevention. [U.S. Bureau of Mines. Miners' Circular 5. Washington, 1911.]

—Clarke, J. M. Observations on the Magdalen Islands. [From New York State Museum Bulletin 149, Seventh Report of the Director, 1910. Albany: New York State Education Department, 1911.]

—Clement, J. K., Adams, L. H., and Haskins, C. N. Essential Factors in the Formation of Producer Gas. [Bulletin 7, Department of the Interior, Bureau of Mines. Washington, 1911.]

—Cockayne, L. Report on the Dune-Areas of New Zealand, Their Geology, Botany, and Reclamation. [New Zealand Department of Lands. Wellington, 1911.]

—Cragin, F. W. Paleontology of the Malone Jurassic Formation of Texas, with Stratigraphic Notes on Malone Mountain and the Surrounding Region near Sierra Blanca, Texas, by T. W. Stanton. [U.S. Geological Survey Bulletin 266. Washington, 1905.]

—Craig, E. H. C., Wright, W. B., and Bailey, E. B. The Geology of Colonsay and Oronsay with Part of the Ross of Mull. (Explanation of Sheet 35, with part of 27.) With Notes by C. T. Clough and J. S. Flett. Accompanied by Sheet 35, Geological Survey of Scotland. [Memoirs of the Geological Survey, Scotland. No. 35. Edinburgh, 1911.]

—Crandall, Roderic. Geographia, Geologia, Supprimento d'Agua, Transportes e Açudagem nos Estados Orientaes do Norte do Brazil, Ceará, Rio Grande do Norte, Parahyba. [Ministerio da Viação e Obras Publicas. Inspectoria de Obras Contra As Seccas. Publicação n. 4. Serie I, D, E. Hydrologia, geologia, assumptos geraes. Rio de Janeiro, 1910.]

—Dall, W. H. Contributions to the Tertiary Paleontology of the Pacific Coast. [U.S. Geological Survey Professional Paper 59. Washington, 1909.]

—Da Silva, R. Pereira. Estudos e Trabalhos Relativos Aos Estados da Parahyba e Rio Grande do Norte. [Ministerio da Viação e Obras Contra As Seccas. Publicação n. 12. Serie I, E. Rio de Janeiro, 1910.]

—De Wolf, F. W. Year-Book for 1909. [Bulletin 16, Illinois Geological Survey. Urbana, 1910.]

—Diller, J. S., and Others. Miscellaneous Nonmetallic Products: Advance Chapter from Contributions to Economic Geology (Short Papers and Preliminary Reports), 1910. Part I, Metals and Non-Metals, except Fuels. [U.S. Geological Survey, Bulletin 470-K. Washington, 1911.]

—Dittrich, von M. Allgemeines über die analytische Mineralchemie.

—Doelter, von C. Allgemeine Einleitung. [Verlag von Theodor Steinkopff, Dresden.]

—Duffield, T. A Review of Mining Operations in the State of South Australia during the Half-Year Ended June 30, 1911. [No. 14, South Australia Department of Mines. Adelaide, 1911.]

—Farrington, O. C. Analyses of Stone Meteorites. [Field Museum of Natural History, Publication 151. Geological Series, Vol. III, No. 9. Chicago, June 1, 1911.]

—Fernald, R. H., and Smith, C. D. Résumé of Producer-Gas Investigations, October 1, 1904–June 30, 1910. [Department of the Interior, Bureau of Mines, Bulletin 13. Washington, 1911.]

—Freeman, W. B., and Bolster, R. H. Surface Water Supply of the United States, 1909. Part IX. Colorado River Basin. [U.S. Geological Survey Water-Supply Paper 269. Washington, 1911.]

—Freer, P. C. Ninth Annual Report of the Director of the Bureau of Science, to the Honorable the Secretary of the Interior, for the Year Ending August 1, 1910. [Manila, P.I., 1911.]

—Gannett, H. The Areas of the United States, the States, and the Territories. [U.S. Geological Survey Bulletin 302. Washington, 1906.]

—Gee, L. C. E. Northern Territory. General Report on Tanami Goldfield and District (North-Western Central Australia). [Adelaide: Government Printer, 1911.]

—Geological Commission of the Colony of the Cape of Good Hope. Fourteenth Annual Report of the, 1909. [Cape of Good Hope Department of Agriculture. Cape Town, 1910.]

—Gilmore, C. W. A New Fossil Alligator from the Hell Creek Beds of Montana. [No. 1860, from the Proceedings of the United States National Museum, Vol. XLI, pp. 297–302, with Plates 26–27. Published September 9, 1911. Washington, 1911.]

—Gordon, C. H. Geology and Underground Waters of Northeastern Texas. [U. S. Geological Survey Water-Supply Paper 276. Washington, 1911.]

—Goss, W. F. M. The Utilization of Fuel in Locomotive Practice. [Reprint of U.S. Geological Survey Bulletin 402. Washington, 1911.]

—GRANT, U. S. Mining and Prospecting on Prince William Sound in 1909. Mineral Resources of the Southern Part of Kenai Peninsula. By U.S. Grant and D. F. Higgins. [Reprinted from Bulletin 442, U.S. Geological Survey. Washington, 1910.]

—GRANT, U. S., AND HIGGINS, D. F. Glaciers of Prince William Sound and the Southern Part of the Kenai Peninsula, Alaska. II, Glaciers of Port Wells, Prince William Sound. [Bulletin of the American Geographical Society, Vol. XLIII, No. 5, 1911.]

—HÄBERLE, D. Ueber die Messbarkeit der Fortschritte der Verwitterung. [Sonderabdruck aus den Jahresberichten und Mitteilungen des oberrheinischen geologischen Vereines. Neue Folge, Band 1, Heft 2, Seite 53–54. 1911. J. Langs Buchdruckerei, Karlsruhe, 1911.]

———. Ueber Kleinformen der Verwitterung im Hauptbuntsandstein des Pfälzerwaldes. [Heidelberg, 1911. Carl Winter's Universitätsbuchhandlung.]

—HAGUE, A. The Origin of the Thermal Waters in the Yellowstone National Park. [Reprinted from Science, N.S., Vol. XXXIII, No. 850, pp. 553–68, April 14, 1911.]

—HAZARD, D. L. Directions for Magnetic Measurements. [Department of Commerce and Labor, Coast and Geodetic Survey. Washington, 1911.]

———. Results of Observations Made at the Coast and Geodetic Survey Magnetic Observatory at Cheltenham, Maryland, 1907 and 1908. [Department of Commerce and Labor, Coast and Geodetic Survey. Washington, 1911.]

———. Results of Observations Made at the Coast and Geodetic Survey Magnetic Observatory at Sitka, Alaska, 1907 and 1908. [Department of Commerce and Labor, Coast and Geodetic Survey. Washington, 1911.]

—HENNEN, R. V. West Virginia Geological Survey County Reports, 1911.—Wirt, Roane, and Calhoun Counties. With accompanying geologic, topographic, and soil maps. [Morgantown, 1911.]

—HOBBS, WM. H. Repeating Patterns in the Relief and in the Structure of the Land. [Bulletin of the Geological Society of America, Vol. XXII, May 10, 1911.]

—HOLMES, J. A. The Sampling of Coal in the Mine. [Technical Paper I. Bureau of Mines. Washington, 1911.]

—HUTCHINSON, L. L. Preliminary Report on the Rock Asphalt, Asphaltite, Petroleum, and Natural Gas in Oklahoma. [Bulletin No. 2, Oklahoma Geological Survey. Norman, 1911.]

—INOUYE, KINOSUKE. Geology and Mineral Resources of Korea. [Memoirs of the Imperial Geological Survey of Japan. Vol. I, No. 1. Tokyo, 1907.]

—Inspectoria de Obras Contra As Seccas. Ministerio da Viação e Obras Publicas. Memorias e Projectos de Açudes. [Publicação n. 9. Serie II, H—Memorias de Açudagem. Rio de Janeiro, 1910.]

—IRVING, J. D., AND BANCROFT, H. Geology and Ore Deposits near Lake City, Colorado. [U.S. Geological Survey Bulletin 478. Washington, 1911.]

—JAMISON, C. E. Mineral Resources of Wyoming. Mining Laws of the State and of the United States. [Bulletin 1, Series B. Cheyenne, 1911.]

—JOHNSON, J. P. The Pre-Historic Period in South Africa. [New York: Longmans, Green & Co., 1910.]

—KRAUS, E. A New Jolly Balance. [American Journal of Science, Vol. XXXI, June, 1911.]

—LAMB, W. A., FREEMAN, W. B., AND HENSHAW, F. F. Surface Water Supply of the United States, 1909. Part. VI. Missouri River Basin. Prepared under the Direction of M. O. Leighton. [U.S. Geological Survey Water-Supply Paper 266. Washington, 1911.]

—LAMBE, L. M. On Arctotherium from the Pleistocene of Yukon. [From the Ottawa Naturalist, Vol. XXV, No. 2, May, 1911. Ottawa.]

—LANDES, HENRY. The Road Materials of Washington. [Bulletin No. 2, Washington Geological Survey. Olympia, 1911.]

—LANEY, F. B. The Relation of Bornite and Chalcocite in the Copper Ores of the Virginia District of North Carolina and Virginia. [No. 1835, from the Proceedings of the United States National Museum, Vol. XL, pp. 513–24, with Plates 63–69. Published May 31, 1911. Washington.]

—LAUTENSACH, HERMANN. Die Alpen im Eiszeitalter von A. Penck und Ed. Brückner. [Sonderabdruck aus der Zeitschrift für Gletscherkunde. Band IV, 1909. Berlin: Verlag von Gebrüder Borntraeger.]

—LINGDREN, W. The Tertiary Gravels of the Sierra Nevada of California. [U.S. Geological Survey Professional Paper 73. Washington, 1911.]

—LOEFGREN, ALBERTO. Notas Botanicas (Ceará). [Publicação n. 2. Serie I, A—Investigações Botanicas. Ministerio da Viaçao e Obras Publicas. Inspectoria de Obras Contra As Seccas. Rio de Janeiro, 1910.]

—MARSHALL, R. B. Results of Spirit Leveling in California, 1907 to 1910, Inclusive. (Work in Sacramento, Salinas, and San Joaquin Valleys Done in Co-operation with the State.) [U.S. Geological Survey Bulletin 481. Washington, 1911.]

———. Results of Spirit Leveling in Idaho, 1896 to 1909, Inclusive. [U.S. Geological Survey Bulletin 487. Washington, 1911.]

———. Results of Spirit Leveling in Iowa. [U.S. Geological Survey Bulletin No. 460. Washington, 1911.]

———. Results of Spirit Leveling in Michigan and Wisconsin, 1897 to 1909, Inclusive. [U.S. Geological Survey Bulletin 461. Washington, 1911.]

———. Results of Spirit Leveling in Nevada, 1897 to 1909, Inclusive. [U.S. Geological Survey Bulletin 488. Washington, 1911.]

———. Results of Spirit Leveling in Texas, 1896 to 1910, Inclusive. [U.S. Geological Survey Bulletin 468. Washington, 1911.]

———. Results of Spirit Leveling in Utah, 1897 to 1910, Inclusive. [U.S. Geological Survey Bulletin 489. Washington, 1911.]

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THE EVIDENCE OF THREE DISTINCT GLACIAL EPOCHS IN THE PLEISTOCENE HISTORY OF THE SAN JUAN MOUNTAINS, COLORADO[1]

WALLACE W. ATWOOD
AND
KIRTLEY F. MATHER

Each of the six advances of ice from the Labrador and Keewatin centers during Pleistocene times was presumably accompanied by a similar formation and advance of glaciers in the Cordilleran region of North America. Each of the five interglacial intervals which have been recognized in the Mississippi Valley must have been accompanied by a shrinkage of the ice in the mountains which may or may not have resulted in complete deglaciation of the mountain areas. It is also evident that certain mountain groups, depending largely upon the latitude and altitude, may have been affected by less than the full number of ice formations and advances. Examples have been pointed out among the Uinta Mountains where certain basins that were glaciated during the earlier of two epochs were not occupied by ice during the later glacial epoch.[2]

The difficulty of recognizing and differentiating glacial deposits of distinct epochs in the mountains is somewhat greater than that of identifying deposits of successive continental ice sheets. Each

[1] Published with the permission of the Director of the United States Geological Survey.

[2] W. W. Atwood, *U.S. Geol. Survey, Prof. Paper 61* (1909), 13, 14, 22, 58.

ice advance in a single mountain valley would presumably remove most if not all of the deposits of a preceding advance. In most cases the erosive action of the ice formed during the epoch of maximum glaciation would effectually destroy all evidence of previous glacial epochs. In all cases of distinct glacial epochs which have as yet been worked out among the mountains the morainic materials of the earlier epochs were deposited beyond the reach of all succeeding ice advances.

In each of the higher ranges of the North American Cordillera evidence of recent glaciation is abundant, but in only a few of the ranges have glacial studies been prosecuted with sufficient detail to demonstrate distinct glacial epochs.

In the Bighorn Mountains of Wyoming evidences of two glacial epochs have been found.[1] The earlier of these was slightly more extensive than the later and the time interval between the two must have been considerable. In addition to these two drift deposits certain large bowlders were noted as suggestive of a possibly still older and more extensive epoch of glaciation in that range.

In the Sawatch range similar facts to demonstrate two glacial epochs have been ascertained.[2]

In this region a deposit of huge bowlders has been reported beyond the earliest known glacial drift, and in such relations to the present topography that if proven to be of glacial origin they would demonstrate a third and much older glacial epoch.

In the Uinta and Wasatch mountains morainic deposits of two well-defined epochs of glaciation have been identified,[3] and in the Front range of the Rockies the drift deposits have likewise been referred to two glacial epochs.[4]

In the San Juan Mountains of southwestern Colorado the effects of glaciation have been noted by many observers. In the Telluride, La Plata, Silverton, Needle mountains, and Rico folios evidence of the recent glaciation is presented, and reference is made to certain

[1] Salisbury and Blackwelder, *Jour. Geol.*, XI (1903), 216–23.

[2] Capps and Leffingwell, *Jour. Geol.*, XII (1904), 698–706; Capps, *U.S. Geol. Survey Bull. 386* (1907); Westgate, *Jour. Geol.*, XIII (1905), 285–312.

[3] W. W. Atwood, *U.S. Geol. Survey, Prof. Paper 61* (1909).

[4] S. H. Ball, *U.S. Geol. Survey, Prof. Paper 63* (1908), 83–86; F. L. Ransome, *U.S. Geol. Survey, Prof. Paper 75* (1911), 72–79.

gravel deposits suggestive of glaciation in more remote Pleistocene times. Satisfactory evidence of an earlier epoch of glaciation was found in the progress of the field work for the Ouray folio.[1] It is noteworthy that these deposits on the north side of the range which were undoubtedly formed during an epoch of glaciation preceding the last occupation of this range by ice are apparently of greater age than those made by the "earlier ice" of the mountain groups cited above. They are in harmony with the scattered deposits found in the Bighorn and Sawatch ranges which suggested a third and still earlier glaciation, rather than with the earlier of the two well-defined epochs which have been noted in several of the Cordilleran mountain groups. A fuller statement regarding these deposits will be given later in this paper. More recently, in the Engineer Mountain quadrangle of the San Juan Mountains, evidence of two glacial epochs has been recognized.[2]

Work upon which the present paper is based.—In 1910 the glacial deposits of the La Plata, Animas, Florida, Vallecito, and Pine valleys on the southern and southwestern slopes of the San Juan range were studied in detail and these studies revealed the evidence of two distinct glacial epochs.[3]

In 1911 similar studies in the valleys of Weminuche and Huerto creeks and the Piedra River, on the southeastern, of the Rio Grande on the eastern, and of the Uncompahgre and Dallas, on the northern slopes of the range, have resulted in the finding of evidence which will be presented as proof of three distinct glacial epochs in the history of this mountain group.

Nomenclature.—It is not as yet possible definitely to correlate the glacial epochs among the mountains with those of the continental ice sheets, and even if such a correlation could be correctly made it may prove desirable to have different names for the epochs associated with the two types of glaciation which existed on this continent during the Pleistocene period. Throughout this paper the three epochs now known to have existed in the San Juan area will be referred to by the names which were applied and used in the

[1] Howe and Cross, *Bull. Geol. Soc. Am.*, XVII (1905), 251–74; Cross and Howe, *U.S. Geol. Survey, Folio 153* (1907).

[2] A. D. Hole, *U.S. Geol. Survey, Folio 171* (1910).

[3] W. W. Atwood, *Jour. Geol.*, XIX (1911), 449–53.

progress of the field work. In the selection of the names an attempt has been made to recognize some of the glacial studies which have contributed to the solution of this problem.

The earliest and oldest of the three known glacial epochs is designated the "San Juan glacial epoch"; the intermediate epoch, formerly called the "earlier" or "older," is here called the "Bighorn glacial epoch"; while the most recent and youngest of the three is referred to as the "Uinta glacial epoch."

It is believed that it may also be of advantage to apply names to the interglacial intervals as well, and for that purpose the following names are tentatively proposed: for the interval between the San Juan and Bighorn glacial epochs the term "Uncompahgre interglacial interval" is suggested; and for the interval between the Bighorn and Uinta glacial epochs we may use the term "Animas interglacial interval." These names have been applied because portions of the valleys of the two streams named are good examples of the canyon development accomplished during the interglacial times.

The Pleistocene period in the western mountains would then be subdivided, beginning with the earliest of the known glaciations in that region, as follows:

San Juan glacial epoch.
Uncompahgre interglacial interval.
Big Horn glacial epoch.
Animas interglacial interval.
Uinta glacial epoch.

General features of the San Juan Mountains.—The San Juan Mountains embrace an area of about 3,000 square miles in southwestern Colorado, extending westward from the San Luis Park to within fifty miles of the Utah boundary. North and south the mountainous area varies in width from 25 to 40 miles. The central portion of the region is a group of rugged peaks, many of which are over 14,000 feet in elevation, while the borders of the range slope downward to the plateaus of New Mexico and Utah.

The central mountain mass is formed of igneous rock, both volcanic and intrusive, which during Tertiary times was built up into a great volcanic plateau several thousand square miles in extent. Beneath the volcanics, the sedimentary rocks of Paleozoic

and Mesozoic age dip away from the central portion of the region; in a few of the deeper valleys and near the present borders of the volcanic area, the complex of pre-Cambrian sediments, schists, gneisses, and intrusive rocks upon which the Paleozoic and Mesozoic rocks rest, is exposed. About the margin of the range there are some clastic sediments of Tertiary age.

The range has been maturely dissected by the headwaters of four great streams which have attacked it from every side. On the east the Rio Grande, on the south the San Juan, on the west the Dolores, on the north the Gunnison, each with its many tributaries, has penetrated to the very heart of the mountains. The Rio Grande flows to the Gulf of Mexico, while the other three, finding their way across the plateaus through deep canyons, join the Colorado River and thence empty into the Gulf of California. (See Fig. 1.)

The work of each of these stream systems has been greatly influenced during Pleistocene times by the action of glacial ice. Many of the peaks and divides were notably sculptured by ice action and the valleys in the mountains show the effect of the passage of the glaciers through them. On the surrounding mesas and plateaus there are some glacial deposits and in the valleys beyond the base of the range there are many terraces and benches which may be traced upstream to the terminal moraines just within the mountainous region.

The more readily recognized deposits of the two younger epochs will be first described, so that the evidence bearing upon a third and still earlier epoch may be more clearly presented.

The Uinta glacial epoch in the San Juan Mountains.—During Uinta times ice collected at the heads of nearly all of the larger streams in the San Juan area and moved for a greater or less distance into the valleys below. In the heart of the range only the higher peaks and divides were above the glaciers, but as the ice moved outward from the central portion of the range it became concentrated in the larger valleys and left much of the region unglaciated. In each of the valleys thus far studied the glaciers of the Uinta epoch were strictly limited to the valleys and in no case did they extend far beyond the foothills of the range.

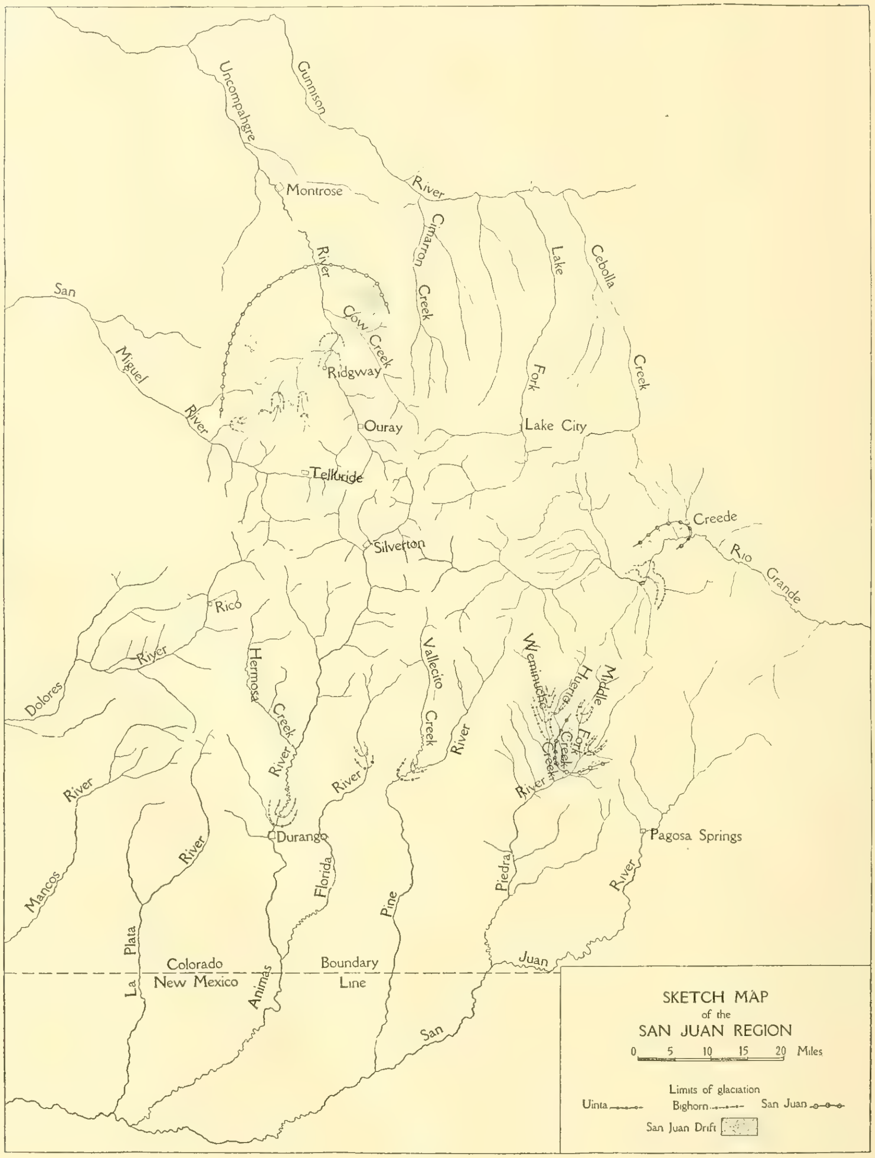

SKETCH MAP
of the
SAN JUAN REGION
0 5 10 15 20 Miles
Limits of glaciation
Uinta
Bighorn
San Juan
San Juan Drift
Gunnison River
Uncompahgre River
Montrose
Cimarron Creek
Lake Fork
Cebolla Creek
San Miguel River
Cow Creek
Ridgway
Ouray
Lake City
Telluride
Silverton
Creede
Rio Grande
Rico
Dolores River
Hermosa Creek
Vallecito Creek
Weminuche Creek
Huerta Creek
Middle Fork
Mancos River
La Plata River
Animas River
Durango
Florida River
Pine River
Piedra River
Pagosa Springs
San Juan River
Colorado
New Mexico
Boundary Line

FIG. 1

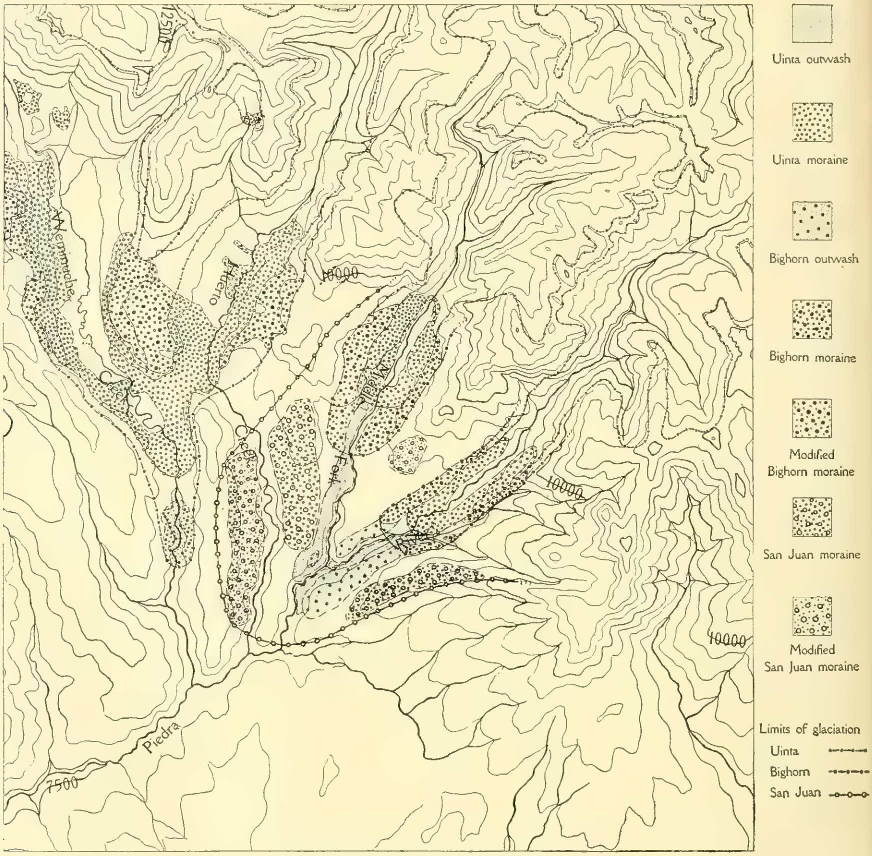
The largest of the glaciers of this epoch was that which occupied the Animas Valley on the south slope of the range. The gathering grounds for this glacier covered several hundred square miles and it had a length of over fifty miles. The terminal moraine deposited when this glacier was at its maximum extent is near Animas City, two miles north of Durango. This moraine consists of two well-marked ridges swinging across the valley floor in broadly crescentic lines. Downstream from the Animas City moraine there are outwash deposits which extend for many miles. Upon one of the terrace remnants of this outwash is situated the city of Durango. Two slightly different levels appear to have been capped with outwash materials at this time and the uppermost of the two is less than fifty feet above the present stream channel.

Similar but smaller glaciers occupied the valleys of the Florida, Vallecito, and Pine rivers, situated east of the Animas. The terminal deposit of the Florida glacier is in the form of a number of low hills or knolls scattered over the valley floor, while the ice in the other two valleys coalesced and the terminal deposit crosses the valley flat of the Pine River a mile below the junction of the two streams.

Still farther east the four large streams which together form the Piedra River show the results of ice occupancy during the Uinta epoch. The terminal deposits in these valleys are likewise well within the foothill zone and, as shown in Fig. 2, are limited to the immediate valley flats. The streams have cut but narrow channels through these morainal barriers.

Another glacier of considerable size occupied the valley of the Rio Grande, extending from well within the Silverton quadrangle to the eastern margin of the San Cristobal quadrangle. South and southeast from Bristol Head at the lower ends of Middle Creek, Trout Creek, and South River (see Fig. 3) there is a very considerable mass of morainic material deposited from the glaciers which, during Uinta times, filled the four valleys mentioned and united in the Rio Grande Valley. This deposit has a typical morainal topography and must aggregate a thickness of 200 to 300 feet in places. Near the middle of the Rio Grande Valley the material is almost entirely that left by the Rio Grande glacier and

it contains great quantities of bowlders of pre-Cambrian rocks—quartzites, schists, gneisses, and granites—which must have been obtained from near the headwaters of the Rio Grande. The débris



Map of the upper Piedra River

Topography from San Cristobal quadrangle and Hayden Atlas.

0 1 2 3 4 5 Miles

Contour interval 500 feet

FIG. 2

transported by the tributary glaciers from the south is largely of volcanic origin.

The third largest glacier of the region during this epoch was that in the Uncompahgre Valley on the north side of the range.

Ice formed in the cirques of the Silverton quadrangle and moved northward by the present site of the city of Ouray to a point fully ten miles downstream from that city where the ice ceased to advance and deposited a remarkable terminal moraine. This is

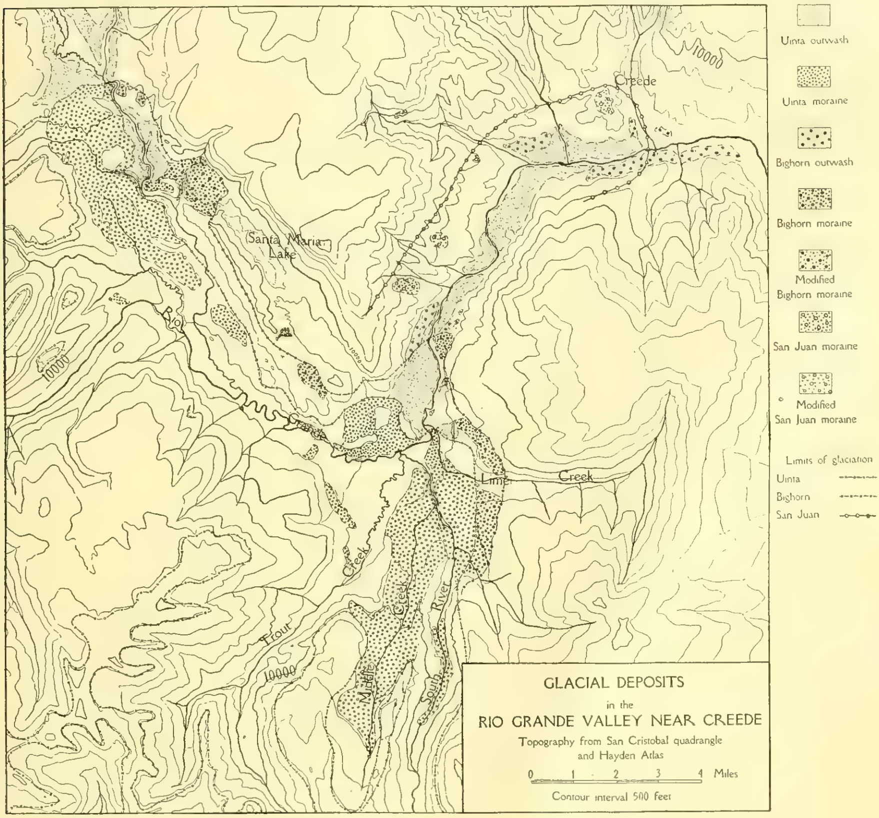


FIG. 3

the largest of the terminal moraines as yet described in the San Juan area; it is over 400 feet in height[1] and forms a crescentic ridge across the valley flat just northeast of the village of Ridgway.

Near the headwaters of Dallas Creek, a tributary to the Uncompahgre from the west, there were small glaciers during the

[1] Howe and Cross, *Bull. Geol. Soc. Am.*, XVII (1906), 254–55; Cross and Howe, *U.S. Geol. Survey, Folio 153* (1907), 7.

Uinta epoch. These glaciers formed in the basins near the north base of Mount Sneffels. The terminal moraines of these glaciers are conspicuous masses of drift in the valley and upstream from these moraines there are other glacial deposits.

The extreme recency of the Uinta glaciation is shown in many ways. The materials of the moraines are fresh and unaltered, retaining in many cases polished surfaces and striae. Post-Uinta weathering and stream erosion are of very limited amount as shown not only by the glaciated rock surfaces so numerous in the upper courses of the streams but also by the character of the glacial débris itself. The streams are still engaged in the task of cutting channels through the drift and clearing it away from their courses, while downstream from the terminal moraines the outwash terraces are never more than a few feet above the present stream channels. Most conspicuous of all, as noted by many observers in the western mountains, is the slight modification which the later glacial deposits have undergone. Typical knob and kettle topographies are present in the drift deposits at many places and small lakes occupy many of the undrained depressions.

The Animas interglacial interval.—The time interval immediately preceding the epoch of glaciation which has just been described was a time of active erosion in the San Juan area. The streams were vigorously engaged in the work of lowering their channels, and canyons were cut beneath the level of the broad valley floors which had received the deposits of the next earlier or Bighorn glacial epoch. The Animas River lowered its channel during this time by more than 300 feet, near the city of Durango, while the valley deepening in the Uncompahgre Valley was even greater. This change in work from that of lateral planation in progress during the Bighorn glacial epoch, to that of active downward cutting, may be attributed to the clearing of the waters following the melting away of the Bighorn ice, but it is probable that this interval of canyon cutting is an evidence of mountain growth during or immediately following the Bighorn epoch. A slight renewal of the domal uplift movements that seem to have affected this region several times during Tertiary and Quaternary times would have rejuvenated streams radiating from the central portion of the

dome. Further physiographic studies in the range will probably yield conclusive data on this problem.

The Bighorn glacial epoch.—Beyond the limits reached by the Uinta ice at its maximum extent there are, in each of the valleys noted above, deposits of glacial drift which prove the presence in these valleys of ice of an earlier epoch. These drift deposits are, in most cases, remnants of the terminal moraines of the next earlier, or Bighorn, glaciers and are found from one to three miles downstream from the Uinta terminal moraines. The greater size of the Bighorn glaciers is also evidenced in some of the valleys by the presence of remnants of lateral moraines on valley slopes at greater elevations than those of the Uinta epoch at those localities.

The remnants of the terminal moraines deposited by the Bighorn ice are in each case situated on rock benches which vary in elevation up to something more than 300 feet above the present stream channels. This relationship is well shown in the Animas Valley where the Bighorn moraine is found on the very prominent rock bench east of the city of Durango and at an elevation of more than 300 feet above the present valley bottom. The northern portion of this rock terrace is heavily mantled with the morainal débris, while downstream from the front of the moraine the terrace is capped with outwash gravels having in places a thickness of at least thirty feet. In each of the main canyons east of the Animas similar conditions obtain.

At the time of the advance of the Bighorn ice Huerto Creek (see Fig. 2) was tributary to the Weminuche through the low sag, now partially filled with Uinta drift, just south of the San Cristobal quadrangle, and the ice in the two valleys, coalescing at this point, moved down Weminuche Creek a distance of three miles below the lower limits of the Uinta drift in that valley. Remnants of the terminal moraine deposits at this point are found on a rock bench 75 feet above the present stream. The small amount of post-Bighorn Valley cutting here as compared with that in the Animas Valley is probably due to several causes. The diversion of the head-waters of Huerto Creek, which will be accounted for later, robbed the Weminuche of nearly half of its former volume; the Animas is a very much larger stream than the Weminuche and is capable of

doing much more work in the same time; the domal movement which caused the renewal of down cutting during the Animas interglacial epoch may have been differential. Eastward from Huerto Creek two other canyons have been studied in which Bighorn glacial deposits have been recognized.

In the Rio Grande Valley the deposits of Bighorn drift are found extending downstream about two miles below the Uinta terminal moraine and are banked against the eastern wall of the Rio Grande Valley a short distance up Lime Creek (see Fig. 3) and southward across the latter to the eastern wall of South River Valley. The conspicuous ridge southeast from Bristol Head on the floor of the Rio Grande Valley, which stopped the further advance of the Uinta ice at that point, is also capped with drift bowlders dropped upon it when it was overridden by the more extensive Bighorn ice. Downstream from the terminal moraine in this valley there are very notable outwash terraces of considerable extent with an elevation of nearly a hundred feet above the present stream channel.

In the Uncompahgre Valley on the north slope of the range similar relations exist between the drift of the two later epochs of glaciation. On the extreme southeast corner of the Uncompahgre plateau near Dallas there is a glacial drift deposit capping the mesa. The bowlders range in size up to three feet in diameter and comprise quartzite, sandstone, shale, tuff, and a variety of volcanic rocks. Some of the stones in this deposit are striated. In this deposit there are also large angular blocks of Dakota sandstone which were certainly not carried by water. They are at present in the midst of the bowlder deposit some hundred feet above the Dakota surface beneath them. The Dakota surface rises gently toward the west and forms the Uncompahgre plateau. The angular blocks could not have attained their present position by sliding or by stream action. They show no signs of stream wear. Up the Uncompahgre canyon the nearest Dakota outcrop is several miles distant, and the only agent that was capable of gathering, transporting, and depositing these blocks in their present position was glacial ice. This fact, combined with the variety of bowlders, their wear and striations, is adequate proof of the glacial origin of this

deposit although it has lost its morainal topography. Since this deposit is on a rock bench several hundred feet above the valley flat and downstream from the Uinta terminal moraine has lead to the interpretation that it is of Bighorn glacial age. Directly across the valley on the hills east of Dallas there are other drift deposits with weak morainal topography which have also been interpreted as remnants of the Bighorn drift. Downstream from these patches of Bighorn moraine there are several remnants of the outwash materials from the ice of this epoch. These outwash gravels cap rock benches at elevations of 300 to 500 feet above the present channel of the Uncompahgre River.

Downstream from the Uinta moraines in the headwaters of Dallas Creek there are remnants of an older series of moraines which have been interpreted as of Bighorn glacial age (see Fig. 4). Associated with these deposits there are still remaining some outwash materials which are believed to have been deposited at the time the moraines were laid down.

Although the glaciers of the Bighorn epoch were as a rule slightly longer than those of the Uinta epoch, in no case did they extend beyond the foothill zone surrounding the range or override the walls of the canyons very far so as to spread out over the bordering lands. The Bighorn epoch glaciers were all of the valley type. The valley trains of the Bighorn epoch were of greater extent than those of the later epoch, and the gravel-capped terraces which are remnants of the Bighorn valley floors may be traced for several miles down each of the larger streams radiating from the range.

The amount of valley cutting beneath the level upon which the Bighorn deposits were laid down was much greater than that which has been accomplished since the last retreat of the ice. The length of the Animas interglacial interval, which immediately preceded the Uinta glaciation, was certainly several times as long as the time since the last melting away of the ice.

The Uncompahgre interglacial interval.—Adjacent to the range on the south there are extensive bowlder-capped mesas high above the outwash material of the Bighorn epoch. The Florida and Fort Lewis are good examples of such mesas. Similar gravel-

capped elevations have been noted at many places about the range, and in the Ouray quadrangle such gravel cappings have been mapped as "Earlier Terrace Gravels."[1]

The mesas slope away from the mountains with gradients of 150 to 250 feet per mile; their surfaces are from 500 to 1,000 feet

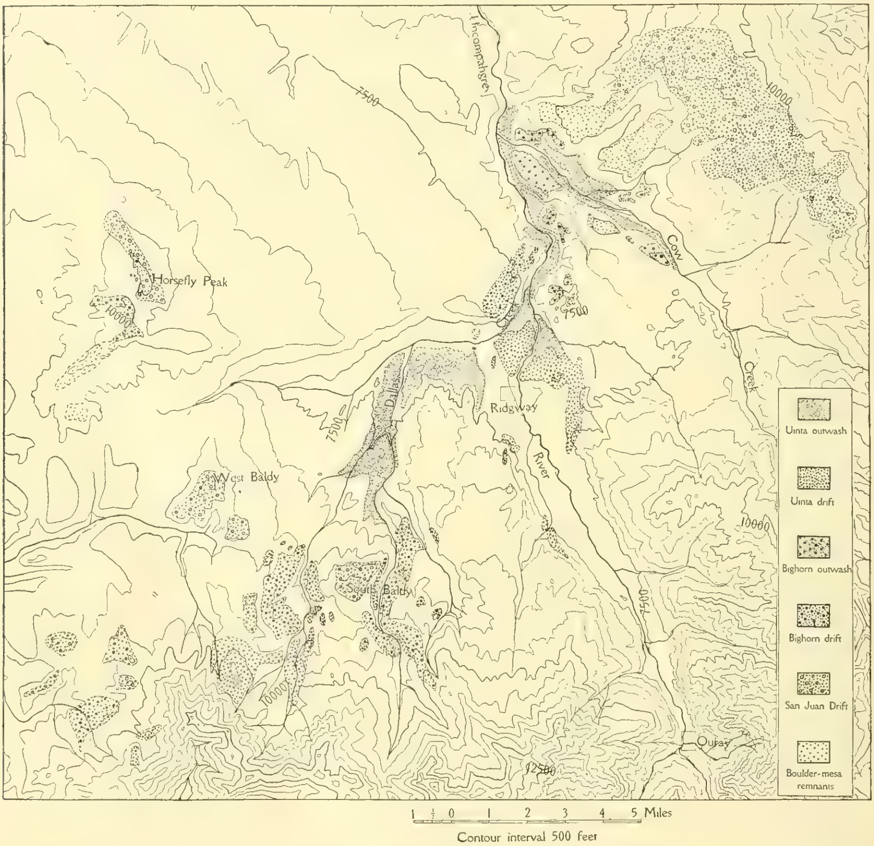


FIG. 4.—Glacial deposits at the northwest margin of the San Juan Mountains. Topography from the Montrose Quadrangle.

above the present valley flats, and in each case they are at elevations 50 to 200 feet above the adjacent terraces which bear the Bighorn outwash gravels. Wherever it has been possible as yet to observe their relations to remnants of San Juan drift it has been noted that

[1] Cross and Howe, *U.S. Geol. Survey, Folio 153* (1907).

the mesa surfaces are cut into and below the elevations now mantled with the drift of that, the oldest known, glacial epoch. The bowlder-gravels capping the mesas may be found to be, in parts outwash materials from the early glaciers, and, in part, remnants of a widespread deposit made by the larger streams during and perhaps immediately following the San Juan glacial epoch. They may belong in part to the Uncompahgre interglacial epoch.

Some time after the retreat of the San Juan ice the streams began to erode their channels vigorously in the mountainous portion of the area. Much of the material removed from the upper courses of the streams was deposited as great alluvial fans on the bordering plateaus. This process of canyon deepening in the mountains continued until much of the San Juan area was skirted by a piedmont alluvial plain sloping gently away from the central mountain region.

The dissection of these bowlder-capped mesas began as the effects of rejuvenation advanced upstream through the bordering plateau country, and continued until the inauguration of the Bighorn glacial epoch, when the streams again became heavily loaded with débris and began to aggrade their valleys.

The distribution of the deposits that have been interpreted as belonging to the San Juan glacial epoch is such as to indicate with certainty that the great canyons through which the glaciers of the two later epochs moved did not exist as deep troughs at the time of the earliest known or San Juan epoch. Deposition of bowlder-gravels may have characterized the earlier part of the Uncompahgre interval, but it is evident that before the close of the interval great canyons had been developed. This interval was certainly much longer than the Animas interglacial interval and it may have been marked by many changes in physiographic conditions which have not as yet been determined.

The valley forms suggest that the streams had reached a temporary base level and had somewhat widened their valleys by lateral planation in the lower country before the formation of the Bighorn glaciers. The rock benches which are now capped with Bighorn moraine and outwash were then the floors of the valleys.

The San Juan glacial epoch.—Evidence bearing on a third and much earlier glacial epoch has now been secured from three widely

separated portions of the range (1) near the southeast margin in the valleys of the Piedra and certain of its tributaries, (2) at the eastern side of the range in the Rio Grande Valley, and (3) at the northwest in association with the valley of the Uncompahgre and the plateau of the same name. The first suggestion that there was evidence of a third and much earlier epoch of glaciation in this range than had been determined in the Cordilleran region of North America was secured from the paper by Howe and Cross, so often referred to above.[1] From an inspection of the maps it appeared that if the mantling material of Horsefly Peak was indeed glacial that it must belong to an epoch of glaciation far removed in time from the known glacial epochs of the western mountains. The first determination by the present authors of three distinct epochs was, however, made near the headwaters of the Piedra River. In that region, on the intervalley areas, high above the present streams and beyond the terminal moraines of the two later epochs, there are much older glacial deposits. The distribution of these deposits has been indicated on Fig. 2.

The morainic deposits on the west side of Huerto Creek, a few miles above the Piedra, are, in part, fully 1,000 feet above the Huerto stream channel. They mantle the slope toward the stream in great landslide masses which appear to have come down in very recent times. In this deposit there are bowlders up to 9 feet in diameter and striated material is not uncommon. On the ridge between Huerto and Spring creeks the ancient glacial bowlders occur in abundance and in association with them there is a considerable body of finer drift. Some of the stones in this drift are striated. The deposit on the west side of Huerto Creek appears to have come from the headwaters of the Piedra to the north eastward, and it is inferred from the relationship of these deposits, from the absence of the marks of glaciation in Huerto Creek canyon, and from the distribution of other deposits interpreted as of the same age, that the ice which left these deposits advanced over a surface which corresponded to the elevation of the intervalley ridges, and that the thousand-foot canyon of Huerto Creek has been excavated since the melting away of that ice.

[1] *Bull. Geol. Soc. Am.*, XVII (1905), 251–74.

Another large remnant of the San Juan drift occurs on a ridge 1,000 feet above the Piedra and on the south side of that valley. Many of the bowlders in this deposit range from 5 to 10 feet in diameter and a few are known which reach 25 feet in diameter. As the dissection of the country has progressed since the San Juan glacial epoch these bowlders have rolled down the valley slopes.

From the distribution of these deposits the San Juan ice in this portion of the range must have been a large piedmont glacier which extended at least six miles beyond the mountains and had an areal extent on the lowlands of at least 30 square miles. The ice of Middle Fork, the Piedra, and several smaller canyons appears to have united to form this ancient glacier. The relief in this region during the San Juan epoch must have been much less than that of today.

The complete physiographic map of this region has not been completed because of the need of a good topographic base, but it appears from an examination of the region that the San Juan glacial deposits are above and older than the bowlder mesa horizon, which it is believed has been correctly determined in this outlying country.

The oldest drift yet found in the valley of the Rio Grande occurs on the north side of the valley high above the stream, at points between the moraines of the Bighorn epoch and the city of Creede. The fact that these deposits are high above the present valley and not on the intermediate slopes appears to have special significance. If the modern valley had been excavated at the time the San Juan ice there would surely have been remnants of the drift left somewhere on the lower slopes in protected spots. Just east of the San Cristobal quadrangle this ancient glacial drift is found nearly 2,000 feet above the present valley. Near Creede the deposit is represented by a scattering of bowlders on the ridge just west of the city. These bowlders have probably been reworked and let down somewhat from the position where they were left by the ice. This older drift is not difficult to recognize in the Rio Grande Valley because of the presence in it of crystalline rocks which must have come from the western margin of the San Cristobal quadrangle or from still

farther west. The probable form of the San Juan glacier which advanced down the Rio Grande Valley is indicated on Fig. 3.

At the northwest margin of the range the San Juan glacial drift is associated with the valley of the Uncompahgre River which has its source in the mountains south from Ouray. In its upper course the stream flows through a deep canyon cut between some of the highest mountain peaks of the range, but below Ouray the valley widens and above the broad open floor there are terrace remnants characteristic of the valleys in the plateau country bordering the mountains.

Between Ridgway and Montrose the western slope of the valley is formed by the eastern escarpment of the Uncompahgre plateau. To the east, in the low country, the valley is bordered by low hills and mesas. Ten miles due west from Ridgway the divide between the Uncompahgre and the San Miguel rivers is marked by a line of hills rising above the surrounding plateau surface. The highest of these is Horsefly Peak, a hill composed of Mancos shale held up above the surrounding mesa by a protective capping of a heavy bowlder deposit. As noted by Howe and Cross[1] Horsefly Peak and the hills adjacent to it

> are covered so thickly by pebbles, bowlders, and blocks of volcanic material, often 10 or 15 feet in diameter, that in many places the hills have the appearance of being entirely composed of the detritus. The material was derived almost entirely from known late volcanic flows and breccias of the mountains and appears to have been once partly rounded or subangular, but has been much modified in form through weathering. In addition to the late volcanic rocks, there is a little granite and Algonkian quartzite, probably derived from an early Tertiary conglomerate, which in age immediately precedes the volcanic rocks and which is known to occur in the mountains to the south and east. The mass of the hill beneath the gravel is composed of Cretaceous shales resting on the Dakota sandstone, which forms the capping formation of the plateau, and it is probable that many of the moraine-like hillocks and depressions resembling kettle-holes may be due to the uneven erosion of the shales, but in a few places it is possible that true morainic forms exist, although much modified by erosion and weathering.

Similar deposits occur on West Baldy, 5½ miles south of Horsefly Peak, as noted by Howe and Cross, as well as on South Baldy, a few miles to the southeast, and on several hills rising above the level of Hastings' Mesa to the southwest, as shown in Fig. 4. At each of

[1] *Bull. Geol. Soc. Am.*, XVII (1905), 261–62.

these localities these deposits suggest by their physical and lithological heterogeneity, by their lack of assortment, subangular stones, by huge bowlders up to 25 feet in diameter, and topographic situation that they are of glacial origin. At one locality over an area of about one square mile there is an old morainic topography, and on Horsefly Peak, West and South Baldy striated stones were found. The striae were all found on surfaces that had not been exposed. Most of the striated stones found were small, but on the underside of a huge bowlder on South Baldy, Professor R. D. Salisbury found a remarkable example of a smoothed, polished, and striated surface. There is no question but that the material is of glacial origin.

Landslides have frequently affected the disposition of these earliest glacial deposits, but this later topography can be easily distinguished from the morainic topography. Scattered over the mesa surface to the east and northeast of Horsefly Peak there are several small deposits of bowlders which point to a former much more widespread deposit of glacial drift.

On the eastern side of the Uncompahgre Valley between Cow Creek and Cimmarron Ridge there are extensive bowlder deposits which have now been referred to the San Juan epoch of glaciation. The portion of this deposit which lies within the Ouray quadrangle has been mapped in the Ouray folio as "earlier moraine" and the same formation extends some distance north of that quadrangle. The deposit is similar to that at Horsefly Peak as far as the size and assortment of the bowlders is concerned, although no quartzites and very few granites were observed there. In one locality on Burro Creek a good section of the bowlder-gravels is exposed and here it is seen that the bowlders are imbedded in a typical bowlder-till.

The components, arrangement, and topographic relations of these several deposits on the north side of the range show that they are remnants of a once more widespread formation which covered a large area in this vicinity. The size and distribution of the materials composing the detritus, the fact that these huge bowlders have been transported many miles, and the glacial markings which some of them bear, point unmistakably to their glacial origin.

The position of these drift deposits, on and near the divides between the present drainage channels, and in front of the present mountain spurs, is in sharp contrast to that of the deposits referred to the Uinta and Bighorn glacial epochs. The latter are restricted to the present valleys and are much nearer the present mountain front. It is therefore evident that these outlying and somewhat scattered bodies of drift must be the work of the earlier and more widespread body of ice which has been referred to as the ice of the San Juan glacial epoch.

The great age of the deposits made during the San Juan epoch is, in a general way, attested by their location on the present divides. Hundreds of square miles of surface, between the mountains and the remnants of San Juan drift, have been entirely cleared of glacial débris, and notable canyons now separate the mountains from the isolated hills capped with San Juan glacial bowlders. Furthermore, some of the bowlders in the San Juan drift are from formations which formerly covered the neighboring mountains but have since been removed from all but a few summits. It is quite certain that these formations were much more widespread at the time of the formation of the San Juan ice and, therefore, that the relief in the mountains was much less than at present.

On the southern side of the range in the Piedra Valley drift of this oldest epoch which came from the mountains at the head of Middle Fork and the main Piedra River is now separated from the mountains by the 1,000-foot canyon of the Huerto River which must be entirely of post-San Juan age. The deposits capping Horsefly Peak and West Baldy are now separated from the mountain front by the drainage of Dallas and Leopard creeks which have lowered their channels far below the surface upon which the ice of this epoch rested. South Baldy and other elevations to the west that are capped with San Juan drift are distinctly separated from the main mountain front by erosion depressions.

In general, erosion since the San Juan glacial epoch has been so complete and widespread that only those deposits which were situated where conditions were most favorable for their preservation have escaped removal. This is well illustrated by the conditions at Horsefly Peak. Although the drift there has been responsible

in large measure for the preservation of the shale upon which it rests and for the existence of the peak, the shale in turn has been protected from erosion by the underlying Dakota sandstone which forms the surface of most of the Uncompahgre plateau and has delayed the headward growth of valleys that threaten the Horsefly Peak region. Erosion into the Dakota sandstone is still in the stage of extreme youth, while nearly all of the overlying Mancos shale has been removed. This most remarkable plateau of the San Juan district is a very fortunate place for the preservation of a drift deposit through long periods of erosion, and it is on just such surfaces that other remnants of this ancient glacial formation are most likely to be found.

Still more striking are the facts which may be deduced from the composition of the drift bordering the Uncompahgre Valley. The bowlders, as already noted, are almost entirely composed of late volcanic rocks with only a very few fragments of quartzitic and granitic rock. The latter are believed to have been derived from the bowlders of the Telluride conglomerate and their extreme rareness is in sharp contrast to the great proportion of similar bowlders found in the Uinta and Bighorn drift of the Uncompahgre Valley. The quartzites of the two more recent glacial deposits are in the main derived from the Uncompahgre quartzite of the Uncompahgre canyon south of Ouray, and the absence of bowlders from this formation in the drift of the San Juan epoch indicates that this formation was not exposed in this part of the range at the time of the San Juan glaciation. At the present time the Uncompahgre quartzite is found outcropping on the canyon walls, 2,000 feet above the stream. There must have been a canyon deepening at this point of at least that amount since the glaciation responsible for drift on Horsefly Peak and beneath Cimmarron Ridge.

Again, the relation of the San Juan drift near Creede to the broad upland valleys above the present canyons there suggests the extreme age of this earliest of known Pleistocene deposits in the western mountains. The relief of the mountains during this stage must have been very much less than at the present time and the topography must have been characterized by broad, shallow,

mature valleys with low interstream ridges in marked contrast to the rugged peaks, the sharp divides, and the narrow canyons of the present time. The physiographic development of the great scenic features of the San Juan area is therefore largely the work of inter- and post-glacial times.

The valley deepening in the San Juan Mountains since the San Juan glacial epoch must be reckoned in thousands of feet. The Uncompahgre interglacial epoch between the San Juan and Bighorn glaciations must have been several times as long as the Animas interglacial epoch. It is probable that the long period of erosion following this earliest glaciation was not a time of continuous valley deepening. In addition to the depositional interval during which certain high mesas were mantled with bowlders there may have been other epochs of glaciation which intervened between the glaciations of the San Juan and Bighorn epochs but which have left no permanent record. The Uncompahgre interglacial epoch may not be in a strict sense an *interglacial* epoch but may include one or more glacial epochs as well.

Comparing the deposits of these three known glacial times in the San Juan district it is at once seen that the earliest is in striking contrast to the two younger ones in point of area covered and distance from the mountain front attained by the ice. The glacier which extended north from the range to some distance beyond Horsefly Peak should probably not be called a valley glacier. The San Juan ice on the south side of the range was not restricted to a valley, for it extended some distance beyond the mountain front as a great piedmont glacier. The wide area covered by ice at this time seems to indicate a period of far more extensive glaciation than that of the two epochs of valley glaciers, and it is probable that during San Juan glacial epoch much of the mountain country was covered by an ice-cap, while piedmont glaciers deployed over the surrounding plateau lands.

Relation of glacial epochs to physiographic stages in the history of the San Juan mountains.—The physiographic stages in the late history of the San Juan mountains have been worked out in some detail[1] on the south and southwest sides, and in part on the north

[1] W. W. Atwood, *Jour. Geol.*, XIX (1911), 449–53.

side of the range. In outline these stages are as follows: At some time subsequent to the deposition of strata of Wasatch (Lower Eocene) age, and probably near or at the close of the Tertiary period, the San Juan region was reduced to an almost base-leveled condition. Only a few elevations remained as monadnocks above the peneplain upon which streams with gentle gradients were depositing at places a thin mantle of remarkably well-rounded and waterworn quartzite and jasper pebbles. The cycle of erosion which developed this extremely old-age topography was closed by a general uplift in the district, which was emphasized in the San Juan dome. Dissection of the peneplain began in the uplifted dome area and resulted in the formation of great alluvial fans, composed of bowlders as well as gravels, upon the peneplain fringing the dome. At the same time rejuvenation was working upstream across the broad plateau and as soon as this headward erosion had reached the margin of the dome the growth of the great alluvial fans ceased and their dissection began. Remnants of this gravel- and bowlder-capped peneplain are now found as the summit elevations in the mountains and upon the neighboring plateaus.

Below the peneplain level there are other broad bowlder-capped mesa-like forms which appear to represent the base to which the streams worked when the peneplain was first dissected. The bowlder-capped mesas noted in the paragraph descriptive of the Uncompahgre interglacial epoch are typical of this bowlder-mesa stage in the dissection of the area. Another uplift associated with the more or less continuous growth of the mountains deformed the graded surfaces of the bowlder-mesa stage, again rejuvenated the streams, and opened another cycle of erosion. The surfaces to which the streams then worked have been referred to in the studies on the south side of the range as the graded surfaces of the Oxford stage. Beneath these surfaces the streams have cut comparatively narrow valleys.

The problem of the relationship of the epochs of glaciation to the stages in the erosion history of the range is of special interest. The available data make it possible to present a tentative or working hypothesis for the solution of this problem.

On the northern slopes of the range between Cow Creek and

Cimmarron Ridge, and on the west of Horsefly Peak, the San Juan drift lies above and beyond fairly extensive bench surfaces covered with bowlder-gravels. These surfaces slope gently toward the Uncompahgre River. Their extreme evenness, as well as the size and assortment of the bowlders capping them, attest to their origin as graded surfaces of erosion upon which a bowlder deposit was made. These bowlder-covered surfaces are below, and appear to be cut into, the drift deposits and therefore are younger than the drift. It is believed that these surfaces are remnants of the graded surfaces developed during the bowlder-mesa stage of mountain dissection. If this is true the glaciation of the San Juan epoch was one of the incidents which took place during dissection of the late Tertiary peneplain previous to the development of the bowlder-mesas.

On the south side of the range the Bighorn moraines and outwash deposits are found adjacent to the graded surfaces of the Oxford stage near the Pine, Florida, and Animas valleys. The relations there indicate that the Oxford stage of mountain dissection was soon followed by the glaciation of the Bighorn epoch. During the Uncompahgre interglacial epoch the graded surfaces of both the bowlder-mesa and Oxford stages were developed. The Animas interglacial epoch was not of sufficient duration for the formation of great erosional features, but was brought to a close by the Uinta glaciation before the streams had again reached a temporary base level.

Comparison of the glaciation in the San Juans with that of the adjacent mountains.—A comparison of the glacial deposits now known to exist in the San Juan mountains with those reported from the neighboring mountain ranges of Colorado and Utah, as referred to in the opening paragraphs of this paper, shows that the two glaciations of those ranges, known as the "earlier" and "later," are to be correlated with the Bighorn and Uinta epochs as above defined. In the mountain ranges from which two glacial epochs have been reported it is noted that the moraines of each epoch are limited to the immediate valleys and that the earlier is only slightly more extensive than the later. They bear the same relation to each other and to the topographic features of each region as that which characterizes the Bighorn and Uinta deposits of the San Juan mountains.

On the other hand, certain outlying bowlder deposits, recognized in the Uinta mountains by the senior author and in the Bighorn and Sawatch ranges by other observers, which there suggested a third and earlier glacial epoch, would appear to correspond closely to the deposits made by the ice of the San Juan epoch. Like the drift of that stage, as recognized in the San Juans, the bowlder-gravels noted in these ranges occur in patches at some distance from the mountain front and situated on or near divides. It is probable, then, that drift of the San Juan glacial epoch will be recognized in other ranges of the western Cordillera, and it is hoped that additional data may be secured bearing on the amount of Pleistocene and post-Pleistocene erosion in this portion of North America.

THE OLD EROSION SURFACE IN IDAHO: A CRITICISM

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In another part of this volume,[1] Mr. Joseph B. Umpleby describes an old peneplain in the northwestern mountain states, and discusses the evidence bearing upon its age. The original planation was so nearly completed that comparatively few monadnocks were left. The surface truncates folded sedimentary and metamorphic rocks intruded by batholiths of granite, thought to be of Triassic or older age. Since it was made, the plain has been lifted into a plateau and then intrenched by systems of valleys, some of which are as much as 5,000 feet deep. In many places this process has completely destroyed the old peneplain, but in some parts of central Idaho it has left flat-topped remnants of considerable area. By putting together various observed facts, the author reaches the conclusion that the peneplain was made during the Eocene period, that it was then uplifted and the great valleys excavated during the Oligocene, and that in the bottoms of these depressions, lake beds were deposited in Miocene time.

I do not question the identification of the flat-topped remnants and accordant summits as parts of an old elevated peneplain, and it is evident that, as the author says, the plain was developed after the deformation of the strata about the close of the Cretaceous period. It does seem to me, however, that the facts given by the author himself, and others which may be noted here, lead necessarily to quite different conclusions regarding the age of the plain.

The first point in the author's chain of argument to prove the Eocene age of the peneplain is that so-called "lake-beds" of Miocene age were deposited in the valleys excavated in the old plateau after it was elevated. It is a fact that continental deposits of various ages are now found lining the bottoms of large depressions rather generally throughout the Rocky Mountain region, but there are

[1] *Journal of Geology*, XX, No. 2 (1912), pp. 139–47.

several ways in which such conditions may come about. One method is the deposition of the sediments in the bottoms of the valleys, in essentially their present state, as suggested in the article. Again where weak materials have been down-folded or down-faulted between masses of harder rocks, they may be eroded to a lowland on account of difference of resistance to denuding processes. Cases of this sort are well known in the Colorado park region and have been pointed out recently by Davis.[1] A third hypothesis is that the broad valleys occupied by the sediments were excavated and filled before the old peneplain was made. It is clear that if through differential changes of level such filled valleys came to lie below grade level for the streams of the planation period, the sediments could not be wholly removed, but would be as permanent as the most resistant rocks of their surroundings. The Cambrian sediments in the Baraboo Valley of Wisconsin illustrate the principle. If the author has considered these various possibilities, the paper presents no evidence to show that the first hypothesis has any advantage in this case over the second or the third.

The second point made is that the Oligocene period should be allowed for the development of the broad valleys in which the Miocene sediments are supposed to have been deposited. It may be pointed out here that most of the sediments mentioned are believed to be late Miocene, according to Osborn's[2] recent classification, so that it may be permissible to add the earlier part of the Miocene period to the time allowed for the process. Furthermore, erosion proceeds at such different rates under different circumstances, that it is quite impossible to estimate the amount of time necessary for the intrenchment of the Idaho plateau. It may be questioned whether the early Miocene epoch would not suffice, or why, on the other hand, it might not be necessary to add the Eocene to the Oligocene, to account for these valleys. Surely no trustworthy determination of the age of the peneplain can be attained by allowing a geologic period for a process of unknown time requirements.

[1] W. M. Davis, "Front Range in Colorado," *Annals of the Association of American Geographers*, I, 1912, p. 43.

[2] H. F. Osborn, "Genozoic Mammal Horizons of the West," *U.S. Geol. Survey Bull. 361*, 1909.

In the opinion of the author, there is a significant relation between the position of this dissected plateau and the bodies of Eocene sediments in the north Rockies and plains adjacent on the east. The inference is made that these sediments could not have been produced by the dissection of the plateau after it was elevated, partly because the volume of material obtainable from such dissection would be supposedly insufficient, and partly because the drainage seems to have been westward rather than eastward, since the uplift.

In the first place, it seems evident that no sufficient quantitative study has ever been made of the volume of either the Eocene sediments or the material removed in dissecting the plateau, to give the first argument any considerable weight, especially as we do not know to what extent other regions to the north, east, or south may have contributed sediments. As to the second point also, it may be said that no connection has been shown between the Eocene strata and the source of the sediments, and that it seems within the bounds of probability that material may have come from several other directions as well as from the west. In this connection I may point out that Mr. Umpleby's map, showing the distribution of sediments of Eocene age which he thinks may have been derived from the peneplain, includes large outcrops of the Fort Union and correlative formations. Yet the Fort Union in the north Rockies has been upturned, folded, and beveled off, and upon its trunkated edges the Lower Eocene strata were subsequently deposited. It would therefore seem necessary to believe that the Fort Union formation was deposited before the completion of the deformative movements which the author rightly thinks preceded the cycle of erosion represented by the peneplain.

For these reasons I can see but little value in the train of argument by which the author reaches the conclusion that the peneplain furnished the material for the Eocene sediments and which leads him to say: "That the plateau surface is of Eocene age, there seems to be little room for doubt." In view of the fact that several interpretations other than those suggested by the author may be applied to the observed data, it seems to me that there is very large room for doubt. There are, indeed, some additional facts

which are matters of general knowledge, that seem to indicate a much later age than Eocene for the plateau surface described by Mr. Umpleby. These necessitate a short introduction for the sake of clearness.

It is said that "faulting and folding have affected the plateau area of central and eastern Idaho since its last elevation, but through all, the integrity of the old surface has persisted in a remarkable degree." In the preceding paragraph, however, it is pointed out that the remnants of the peneplain do not vary greatly in altitude, the maximum being 10,000 feet in central Idaho and from that falling off very gradually to 8,000, 7,000, and even 5,000 feet at a distance of some 400 miles. Unless there is some other evidence of the supposed folding and faulting, the reader is justified in concluding from the facts presented that the plain has been subject merely to very gentle changes of level, which may be termed mild warping, rather than folding. This very slightly warped condition of the old peneplain should be compared with the much more pronounced deformation visible in the late Eocene sediments and lavas of closely adjacent regions on several sides. Thus, immediately southeast of the region under consideration, the late Eocene and Oligocene beds of northwestern Wyoming have an average dip of 10° and in some places form anticlines with 25° dips on either limb. In addition to this, they have been broken by normal faults of several thousand feet displacement. Again, on the southwestern confines of the central Idaho region itself, the Payette formation, which seems to be safely identified by fossil plants as of late Eocene age, varies in elevation from less than 1,000 feet above sea-level near Weiser, to nearly 6,900 feet above sea-level east of Boise.[1] In the same region the dip of the fine plant-bearing shales, which were doubtless deposited in horizontal position, is now generally 10–15°, and not rarely 25°; while at a one point it rises as high as 80°. Still more striking is the condition in west-central Washington, less than 100 miles from the Republic district in which the old peneplain is said to be readily identified. There the Eocene and even the late Miocene formations

[1] W. Lindgren and N. F. Drake, *U.S. Geol. Survey*, Folio 104, Silver City, Idaho, 1904.

have been shown by Willis[1] and Smith and Calkins[2] to be notably folded into a series of well-marked anticlines and synclines. There seems to be adequate proof in the Snoqualmie quadrangle that this deformation took place about the middle of the Miocene period, so that the case is relieved of the usual difficulties arising from uncertainties of correlation. If the peneplain is Eocene in age it must have suffered the same deformation that produced in these Eocene strata average dips of 10 and in many places of more than 25°. Under those circumstances it could not retain so nearly its original plane character that (barring intrenched valleys) it still differs in altitude only 5,000 feet in 400 miles, or in other words, declivities of but a small fraction of one degree. Rather, the evidence seems to show that this peneplain is much younger than Eocene and probably post-middle-Miocene.

The comments here made upon Mr. Umpleby's article have been called forth by the fact that the peneplain, definitely assigned to the Eocene, is offered to students of Rocky Mountain geology as a valuable "datum plane in broad areas where time relations between the Algonkian and the Pleistocene are otherwise obscured." The peneplain probably has real existence, and may be used as a datum plane to determine the relative ages of other geologic events in the same region; but it should not be regarded as an index of Eocene age, and its exact chronological value will depend upon a more reliable future determination.

[1] G. O. Smith and B. Willis, "Geology of Central Washington," *U.S. Geol. Survey, Prof. Paper 19*, 1904.

[2] G. O. Smith and F. C. Calkins, "Reconnaissance of the Cascade Range," *U.S. Geol. Survey, Bull. 235*, 1904. Also Snoqualmie, Wash., Folio (139), *U.S. Geol. Survey*, 1906.

GLACIATION OF THE ALASKA RANGE[1]

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CONTENTS

GENERAL DESCRIPTION

The Alaska Range is the great crescentic belt of mountains in south-central Alaska that in general forms the divide between the streams which drain southward to the Pacific Ocean and those

[1] Published by permission of the Director of the U.S. Geological Survey.

which join Kuskokwim and Yukon rivers to empty into Bering Sea. The name has commonly been used to include the mountains between the headwaters of Skwentna River and Mentasta Pass, but at its southern end the range is not sharply separated from the Chigmit Mountains of the Alaska Peninsula, although the constituent rocks of the two mountain masses are different and their axes, while parallel, do not coincide. At its east end the Alaska Range is directly continuous with the Nutzotin Mountains. The following descriptions are confined to that portion of the range which lies between meridians 144 and 153 west longitude. Considered as a whole, the Alaska Range is a rugged mountain belt broken by but a few widely separated passes. In the region near the head of the Skwentna three breaks in the range are known which may be crossed by pack animals to the Kuskokwim basin. North of these passes the range becomes of impressive height and ruggedness, culminating in two great peaks, Mount Foraker and Mount McKinley, with elevations of 17,000 and 20,300 feet respectively. Northeast of Mount McKinley the range decreases in height, and at the head of certain tributaries of Chulitna River is broken by one or two passes. East of Nenana River the range once more becomes rugged, the loftier peaks averaging about 8,000 feet in height, although Mount Hayes reaches an elevation of over 13,700 feet. Delta River crosses the range in a low pass, east of which the highest peaks are from 8,000 to 10,000 feet in elevation.

HISTORY OF EXPLORATION

The first white man to cross the Alaska Range was Lieutenant Henry T. Allen, who discovered Mentasta Pass in 1885. West of this pass the mountains were unexplored until 1898, when J. E. Spurr[1] crossed from the Skwentna basin to the Kuskokwim, Eldridge[2] ascended the Susitna and crossed Broad Pass to Nenana River, and Mendenhall,[3] attached to an army exploratory party

[1] J. E. Spurr, "A Reconnaissance in Southwestern Alaska, in 1898," *Twentieth Ann. Rept. U.S. Geol. Survey*, Pt. 7, 1900, pp. 31–264.

[2] G. H. Eldridge, "A Reconnaissance in the Susitna Basin and Adjacent Territory, Alaska, in 1898," *ibid.*, pp. 1–30.

[3] W. C. Mendenhall, "A Reconnaissance from Resurrection Bay to the Tanana River, Alaska," *ibid.*, pp. 271–340.

under Captain E. F. Glenn, crossed Delta Pass. Since that year geologic and topographic surveys have gradually been extended until only small portions of the range are now unknown. Captain Herron, in 1899, discovered Simpson Pass at the head of Kichitna River, and explored a portion of the Kuskokwim lowland. In 1902 Brooks and Prindle[1] traversed the range at Rainy Pass and followed the north slope of the mountains between Kuskokwim and Nenana rivers, and in the same year a topographic and geologic map[2] was made of the south slope between Delta and Mentasta passes. In 1903 Dr. F. A. Cook organized a party for the ascent of Mount McKinley from the northwest. The route already established by Brooks and Prindle from Tyonek to the head of the Skwentna, and thence along the northwest base of the mountains, was followed as far as Muldrow Glacier. From that point the party proceeded in an eastward direction, discovered a pass across a glacier, and emerged on the headwaters of Chulitna River. In 1906 a topographic map was made by R. W. Porter of a portion of the northwest border of Susitna basin.[3] In 1910 the area on the north of the range between Nenana and Delta rivers was mapped[4] geologically and topographically, as was a portion of the range south of this,[5] and during that same summer some explorations were carried on in the high range southeast of Mount McKinley by a party under the leadership of Herschel Parker and Belmore Brown. In 1911 a portion of the northwest border of the Susitna basin was visited by the writer.[6] This gradual completion of reconnaissance surveys has added to our knowledge of the geography of the region until the time seems ripe to summarize briefly the facts with regard

[1] A. H. Brooks and L. M. Prindle, "The Mt. McKinley Region, Alaska," *Prof. Paper U.S. Geol. Survey No. 70*, 1911.

[2] W. C. Mendenhall, "Geology of the Central Copper River Region, Alaska," *Prof. Paper U.S. Geol. Survey No. 41*, 1906.

[3] Published in "The Mt. McKinley Region, Alaska," *Prof. Paper U.S. Geol. Survey No. 70*, 1911.

[4] S. R. Capps, "The Bonnifield Region, Alaska," *Bull. U.S. Geol. Survey No. 501*, 1912.

[5] F. H. Moffit, "Headwater Regions of Gulkana and Susitna Rivers, Alaska," *Bull. U.S. Geol. Survey No. 498*, 1912.

[6] "The Yentna Region, Alaska," *Bull. U.S. Geol. Survey*. In preparation.

to the past and present glaciation of the range as observed by the several geologists who have worked in this field. Such a summarization must naturally be incomplete until the range has been fully mapped.

DISTRIBUTION OF EXISTING GLACIERS

The distribution of existing glaciers in the surveyed areas is shown in the accompanying map, Plate I. In many cases the upper ends of the glaciers lie in unexplored and unmapped portions of the mountains and in these places the probable headward extensions of the glaciers are indicated by a different pattern. The shapes of the unmapped portions will be modified when more exact information is obtainable, but their general position is believed to be approximately as indicated.

As is to be expected, the glaciers reach the greatest size and are most closely spaced in the higher portions of the range, and are smaller, or are wanting altogether in the regions of lower relief. They are all, however, distinctly of the valley-glacier type, and differ in this respect from the glaciers of lower Kenai Peninsula, the Wrangell Mountains, and the coastal range west of Mount St. Elias, which originate in the ice caps and spread from these down the valleys. No extensive ice caps exist in the Alaska Range and each glacier is fed from ice which accumulates in its own basin.

By far the largest glaciers of the range are those of the group which drains from the northwest into the Susitna basin. These head on the slopes of the highest mountains of North America, and by their presence so obstruct the approaches to the crest of the range that an area of several thousand square miles exists which has never been penetrated by man. This group doubtless includes large ice tongues which lie in the unsurveyed area east of Mount McKinley, and are, therefore, not shown on Plate I.

The next important group of glaciers is that which occupies the range for about 50 miles west of Delta River, and which includes many large and vigorous ice streams which do not, however, equal in length or area those in the vicinity of Mounts McKinley and Foraker. The third group lies east of Delta River and the glaciers become smaller and disappear as Mentasta Pass is approached.

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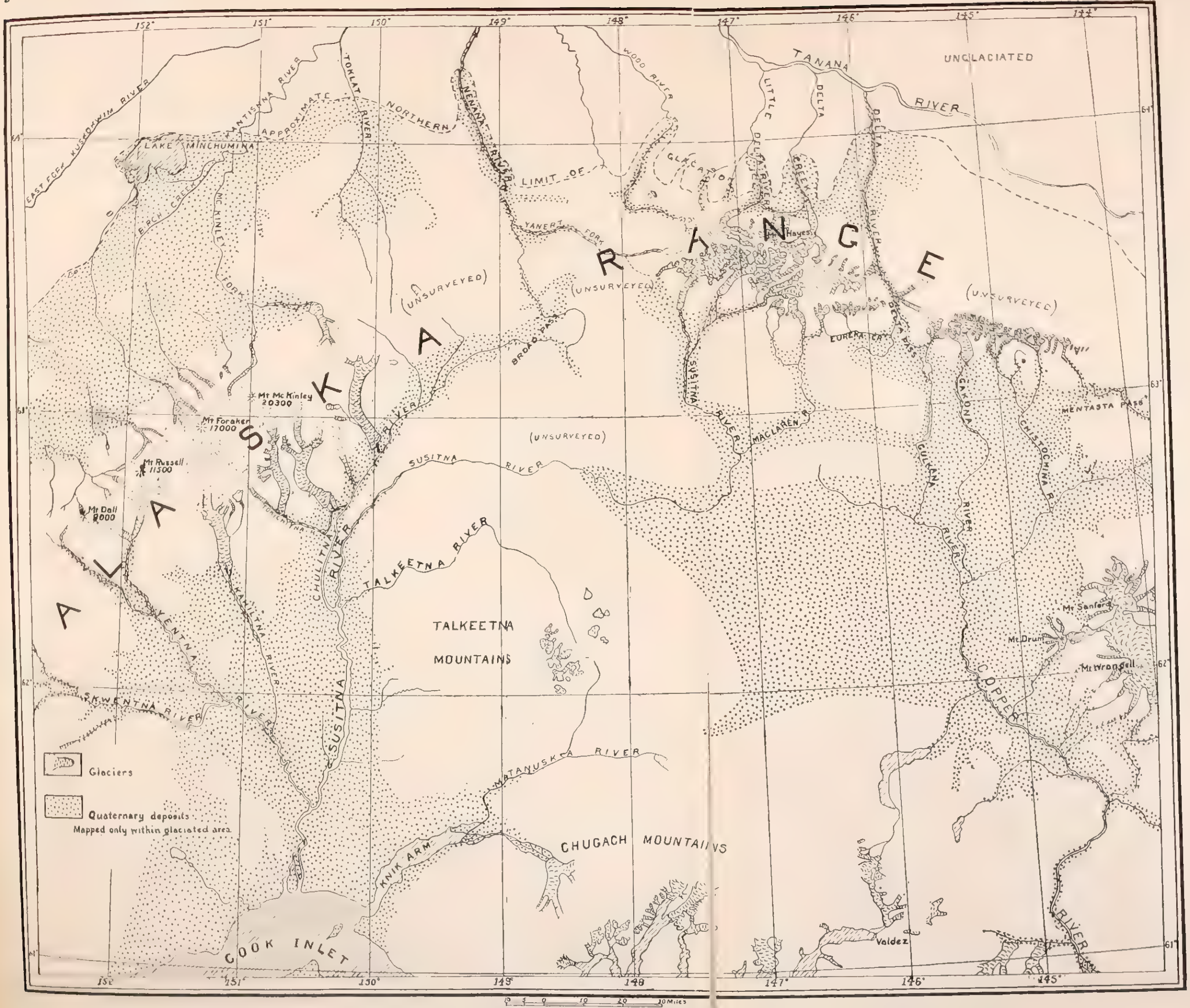

MAP OF THE ALASKA RANGE, ALASKA

The existing glaciers are shown by the conventional symbol. The dotted areas show the distribution of the Quaternary deposits within the glaciated area. The line of dashes indicates approximately the northern limit to which the earlier glaciers reached. Compiled from published and unpublished maps of the U.S. Geological Survey.

The north side of the range is here unsurveyed, but it is reported that the glaciation is less extensive on that side than on the south. The glacial conditions east of the pass and on the north side of the Wrangell Mountains have already been briefly described.[1]

One of the most striking features of the map (Plate I) is the great development of the glaciers on the southward slope of the range as compared with those on the north slope, especially in the vicinity of Mount McKinley. Two factors are believed to be responsible for this unequal distribution of glacial ice. Probably the most important of these is the greater amount of precipitation on the south slope. The moisture-laden winds from the Pacific in passing northward over the range drop most of their content as snow on the south slope. On the interior slope the precipitation is light, and as the amount of snowfall has a controlling influence in the growth and continued activity of glaciers, the southward-moving ice tongues have a great advantage over the poorly fed glaciers on the north. The second factor which favors the Pacific slope glaciers is the greater area of their accumulating grounds. On the south slope the average distance from the crest line to the base of the main range is more than 25 miles, while on the north it is only half this distance. The area of accumulation of those on the north slope is therefore much more restricted and the glaciers are correspondingly of smaller proportion. This unequal development of glaciers holds in other parts of the range as well, in the vicinity of Mount Hayes, and east of Delta River, in regions where there is not the same discrepancy in the area of the collecting fields. The advantage is here given to the southward-moving glaciers by the greater snowfall on that side of the range.

INFLUENCE OF GLACIERS ON THEIR VALLEYS

The erosional effects of glaciers upon their valleys have been so frequently and so fully discussed by many writers that it is unnecessary to dwell upon them here in detail. The most noticeable results of this erosion are the development of the great U-shaped troughs, with the removal of the minor irregularities seen

[1] S. R. Capps, "Glaciation on the North Side of the Wrangell Mountains, Alaska," *Jour. Geol.*, XVIII (1910), 33–57.

in stream-developed valleys, and the truncation of the lateral spurs, giving straight-walled rock troughs. Where the valley makes a bend in its course the ice erosion has developed great sweeping curves so that the glaciers seldom bend at sharp angles. These topographic features, with hanging tributary valleys and a large number of other characteristic and readily recognizable phenomena of glacial erosion, are of service in determining the thickness and former extent of the glaciers in those places where deposits of glacial débris are not to be found.

EVIDENCE OF EARLIER AND MORE EXTENSIVE GLACIERS

The outer limits to which the glaciers of the Alaska Range reached at the time of their maximum extent have for the most part not yet been determined, and much careful detailed work will be required before this limit can be accurately marked. There are certain facts available, however, which show in a general way the area covered by the ice during its greatest development. On the south side of the range no limit of glaciation is shown on the accompanying map (Plate I), for all of the area here shown except the higher peaks and ridges of the more important mountain ranges was covered by glacial ice. The entire Copper River basin was occupied by a great glacier, as has been recognized from abundant deposits of glacial till, which are found throughout the basin at points as far as possible removed from the mountains in which the ice must have originated. The Copper River ice sheet was of great thickness, for it escaped from the basin in a number of directions. It certainly pushed north across Delta Pass, and probably also to the northeast through Mentasta Pass.

To the west it extended into the head of Susitna basin, as is shown by the widely distributed deposits of glacial till in that region. Matunaska Valley heads in a broad divide at an elevation of 3,000 feet, and probably furnished an outlet for the glacial ice to the southwest. The present drainage outlet of the basin, through the Copper River Valley, was also an outlet for a part of the glacial ice, although it is probable that this outlet was not the course followed by the pre-glacial streams and that it was not established till Glacial times. Near the mouth of Chitina River

glacial erratics and glacially sculptured mountain tops show that the great Copper River Glacier at that point overrode mountains 5,690 feet in height. The bed of the glacial valley is here about 500 feet above sea-level so that the glacial ice must at one time have been at least a mile in thickness.[1]

The Susitna Basin Glacier to the westward was continuous with that in the Copper River basin and was of a similar order of magnitude. It filled the broad Susitna lowland and extended southward down the Cook Inlet depression. It may even have reached to the mouth of the inlet, though this has not yet been determined. Some idea of the thickness of this ice sheet may be gained from the fact that north of the mouth of Skwentna River the Yenlo Hills, an isolated group of hills which lie more than 20 miles from the Alaska Range, show glacial erosion and have foreign erratic bowlders at an elevation of 3,300 feet above sea-level, and the ice probably stood several hundred feet higher than the point at which the erratics were found. Along the flanks of the main range there is evidence that the ice surface reaches elevations of over 4,000 feet. The conclusion, therefore, seems unavoidable that at the time of greatest ice accumulation all of the area between the crescent of the Alaska Range and the Pacific Ocean was so covered with glacial ice that only the higher peaks and ridges of the range, and of Talkeetna, Chugach, Kenai, and Wrangell Mountains projected above its surface. It must be remembered, however, that these basins were most favorably situated for large glaciers to accumulate, for they were surrounded on all sides by high mountains from which a multitude of valley glaciers descended to the lowlands. Only a part of the ice originated in the Alaska Range to the north and west.

The restricted development of the earlier glaciers on the interior slope of the Alaska Range as compared with those on the south and east slope is even more striking than the difference which exists between the present-day glaciers on the opposite sides of the range. In considering the northern limit of glaciation as shown on the map (Plate I) it is necessary to have in mind the fact that much of this region is still unsurveyed and that the writer intends to show only in a very general way the borders of the area which the

[1] F. H. Moffit, oral communication.

ice covered. The region north and west of Mount McKinley has been visited by but one surveying party, whose route, however, lay close to the mountains, well within the glaciated area. Brooks[1] states that "the position of the northern front of the ice in the Kuskokwim basin has not been determined but there is reason to believe that it extended as far as Lake Minchumina, or about 30 miles beyond the mountain front." The area between Nenana and Delta rivers was studied by the writer in 1910,[2] and it is believed that the northern limit of glaciation as shown on the map for that region is not greatly in error. The country east of Delta River is still unsurveyed and the ice limit as shown is believed to be only an approximation. It is probable that the same factors which are responsible for the difference in area of glacial ice on opposite sides of the range today and which have already been discussed were operative at the time of the great ice advance, and explain the lesser development of the northward-moving glaciers at that time.

EXISTING GLACIERS

It is not the purpose of this paper to give a detailed description of the multitude of glaciers of the Alaska Range, and such a task would be impossible in the present state of our knowledge of them. Brief descriptions of a few of the more important glaciers which have been observed will, however, be given, especially those which have been visited by the writer in person, and such facts as have a bearing on the recent history of the glaciers, whether they seem to be advancing or retreating, will be recorded.

SUSITNA BASIN

SKWENTNA DRAINAGE

Skwentna River has a number of glaciers at the heads of its various tributaries, but many of them lie in unmapped territory and most of them are not of large size. They are sufficiently numerous and active, however, to keep the river in a turbid state during

[1] A. H. Brooks, "The Mt. McKinley Region, Alaska," *Prof. Paper U.S. Geol. Survey No. 70*, 1911, p. 126.

[2] S. R. Capps, "The Bonnifield Region, Alaska," *Bull. U.S. Geol. Survey No. 501*, 1912.

the summer, and to cause it to build extensive gravel flats in favorable portions of its course.

YENTNA DRAINAGE

Both forks of Yentna River are known to rise in glaciers, those on the west fork being of comparatively small size. The East Fork has its source in two large ice tongues, one of which probably heads on the slopes of Mount Dall, and flows eastward, and the other apparently drains the ice from the southern flank of Mount Russell, and moves in a southward direction. The two tongues meet at their distal ends at an elevation of about 400 feet above sea-level. As seen from a distance, both of these glaciers seem to be relatively free from morainal covering at their lower ends, though they are striped with longitudinal surface moraines. It is not known whether they are advancing or retreating as they have not been critically observed.

Glacio-fluvial deposits and moraines.—The forks of Yentna River both show the characteristic features of glacial streams above their junction, having wide, bare flood plains of sand and gravel, over which the stream flows in an intricate network of braided channels. Below their junction the stream maintains a much more definite channel to its mouth. The valley floor throughout its length, however, is covered with a heavy deposit of glacial outwash, and bed rock outcrops along the banks at only a few places. Some recognizable terminal moraine occurs between the forks for a few miles above their junction, but such deposits are not common. Extensive terraces are developed from the earlier outwash gravels and border the present stream flat in its lower course and are of wide extent between lower Skwentna River and the Yentna (Plate I).

Kahiltna Valley.—Kahiltna River, a tributary of the Yentna, some 25 miles above its mouth, heads in one of the largest glaciers of the Alaska Range. This glacier, which terminates 600 feet above sea-level, has pushed to the edge of the mountains and is expanded somewhat in its lower end into a piedmont lobe which is four miles wide at its face. For the lower 13 miles of its length this ice tongue averages 3 miles in width, has a smooth, even gradient, and is little broken by crevasses except near the edges (Fig. 1). The surface is

unusually free from moraine except for a zone along either side, and white ice shows all the way to the lower end. From favorably situated points along its sides the lower 20 miles of the glacier may be seen, but above this a bend in the valley cuts off the view. A number of tributary ice streams may be seen joining the main glacier from either side. Above the bend the extent of the Kahiltna Glacier is not known, but the great size of the lower portion indicates that the supply basin must be large. It doubtless extends to the crest of the range, and probably includes the southern slopes of Mount Foraker. In all, this glacier is probably at least 35 miles long, and its area, including the many headward tributaries, must be well over 100 square miles.

An examination of the lower end of Kahiltna Glacier shows that the edge has probably been about stationary for a long time. There are no important recessional moraines to be seen, and spruce trees many inches in diameter grow close to the glacier front. The ice edge must, therefore, be as advanced as at any time for at least one hundred years.

A number of streams which themselves head in glaciers enter Kahiltna Valley from the east above the terminus of the glacier, the waters disappearing beneath the ice, or joining the marginal streams. Among these separate, smaller ice fields are the unusually beautiful ones at the heads of Granite and Hidden creeks (Fig. 2).

Glacio-fluvial deposits and moraines: Below Kahiltna Glacier the stream flat shows a bare expanse of gravel bars nearly 4 miles wide at the glacier, and the turbulent river flows across this aggrading flood plain in a complex of constantly shifting channels. The materials are coarsest near the glacier, and become progressively finer down stream. As the distance from the ice front increases the width of the bare flat is diminished by the encroachment of spruce timber and shrubs from either side. About 17 miles from its source the stream gathers into a single channel and enters a postglacial gorge to which it is confined for much of the remainder of its course to the Yentna. Glacio-fluvial terraces are not conspicuously developed along the Kahiltna, but the interstream areas bordering the river are covered by a coating of glacial till and morainic material of varying thickness (Plate I).

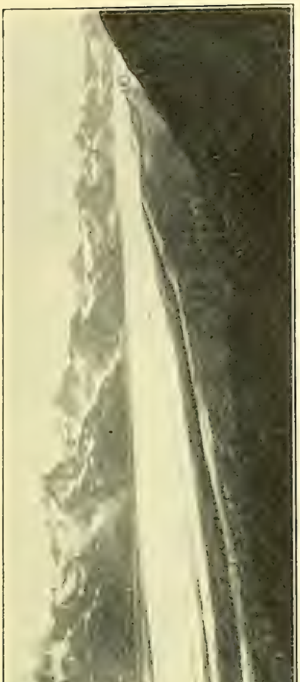

Fig. 1.—View across Kahiltna Glacier from a point 7 miles above the terminus. The glacier is here three miles wide, 1911

Fig. 2.—Cascading glaciers at the head of Hidden Creek, 1911

CHULITNA RIVER DRAINAGE

Tokichitna Valley.—Tokichitna River, a tributary of the Chulitna, receives the discharge from two very large and one medium-sized glacier. The smallest of the three, at the head of the valley, is known as Little Tokichitna Glacier. In its lower part it is nearly a mile wide, and although most of its basin is unsurveyed the glacier has probably a length of at least 10 miles. For several miles above its terminus the surface of this glacier is so covered by moraine that no ice is visible, except along the lower edge where

FIG. 3.—Glacier at the head of Granite Creek, and the rugged mountains between Kahiltna and Tokichitna glaciers.

stream cutting is active. This ice tongue also differs from most valley glaciers in that its sides are not steep, and separated from the valley walls by a depression, even at its lower end. The sides fit flush against the rock valley walls, and detritus from the walls and from steep tributary gulches moves directly out upon the surface of the glacier (Fig. 4). The terminal moraine has been removed almost as rapidly as deposited, and accumulations at the glacier end are small. Trees of considerable size grow only a few hundred feet in front of the ice foot, and directly in its path, so that the glacier cannot have retreated far for a long period of years, or if it has, it has readvanced an equal distance.

Tokichitna Glacier, the principal source of Tokichitna River, joins the east-west valley of that stream from the north, $3\frac{1}{2}$ miles below the end of Little Tokichitna Glacier. It is one of the four largest glaciers of the range, and the borders of the lower 20 miles of the main lobe have been mapped. For this distance the ice stream averages nearly 2 miles in width, with a maximum width of over $2\frac{1}{2}$ miles. The upper unexplored portion lies among the high, rugged peaks of the range, and probably heads on the slopes of Mounts McKinley and Hunter. The total length must be nearly 30 miles.

FIG. 4.—The moraine-covered lower portion of Little Tokichitna Glacier, 1911

The lower end is moraine covered for several miles above the terminus, but above the first bend white ice appears. A heavy growth of spruce timber, close to the front edge of the glacier, shows that the ice edge is now as far advanced as it has been for a long time, and probably indicates a state of equilibrium between supply and wasting.

Near the mouth of Tokichitna River a third, very large glacier pushes out from the mountains from the northwest and spreads out into a bulb-shaped piedmont lobe over 4 miles wide. It is known as either Mud or Ruth[1] Glacier, the former being the name most generally used by the miners of the district, and said to have

[1] F. A. Cook, *To the Top of the Continent.* Doubleday, Page & Co., 1908, p. 90.

been given because of the dirty, moraine-covered character of the terminus.

The lower 16 miles of the glacier, which have been mapped show an average width of nearly 3 miles. In this section the the glacier makes a great bend, and the direction of movement in the principal headward tributary is from north to south.

Glacio-fluvial deposits: None of the large glaciers of the Tokichitna basin have left conspicuous terminal moraines, and this is a result of the topographic position of the glacier ends, situated as they are in confined valleys where the glacial waters are given abundant opportunity to remove the glacial débris as it is dropped by the ice. There are, however, extensive deposits of stream-laid glacial outwash, for although the streams are of large volume they are overloaded, and the aggradation of the valley floor is rapid. Tokichitna River resembles the other glacial streams already described in the development of its aggrading flat, and in the way in which it splits up into many branching channels.

Main Chulitna Valley.—Chulitna River is known to receive drainage from several small and one large glacier from the northwest, above the Tokichitna. The large ice stream, named Fidèle Glacier by Cook,[1] who has published the only description of it, is described by him in the following terms:

> The glacier starts from the northeast ridge of Mount McKinley and flows almost due east for fifteen miles, where it receives a large arm from the north. Five miles southeast of this another arm swells the bulk of the great icy stream, and then it takes a circular course, swinging toward the Chulitna. Its face is about seven miles wide, its length is about forty miles, and the lower ten miles are so thoroughly weighted down by broken stone . . . . that no ice is visible.

Northwest of this glacier there is a stretch of nearly 70 miles of mountains which are almost all unsurveyed, and about the glaciation of which little is known.

HEAD OF SUSITNA RIVER

The headwaters of the main fork of Susitna River, and its tributary the Maclaren, were surveyed in 1910. In the high mountains of this area the glaciers are closely spaced and fill the

[1] F. A. Cook, *op. cit.*, pp. 90–91.

headward ends of all the important valleys (see Plate I). In describing these glaciers Moffit[1] says:

> The most conspicuous of these glaciers are Gulkana Glacier, the glacier in which Eureka Creek and East Fork of Maclaren River head, Maclaren Glacier, and the two large glaciers at the head of Susitna River. The last two are much larger than any others in this region. They are fed by the snow fields in the high rugged country south of Mount Hayes and Cathedral Mountain and are the principal sources of the Susitna, although the glaciers to the east also contribute much water. The westernmost of the two large glaciers is about 25 miles long and more than 1½ miles wide throughout its whole length. The eastern glacier is about 2 miles wide, but is not so long as the first. Maclaren River Glacier is much smaller than either of these, being a little more than 10 miles long and not more than a mile wide at its lower end. Gulkana Glacier and Cantwell Glacier (10 miles northwest of the westernmost Susitna Glacier) are remarkable . . . . in that they contribute water to both Bering Sea and Pacific Ocean drainage.
>
> Most of these glaciers appear to be retreating. Their surfaces are smooth, they end in smooth slopes rather than ice cliffs, and most of them show by the position of terminal moraines that they have receded considerably in recent times.

The peculiar drainage mentioned by Moffit deserves a further word of description. Three glaciers on the south side of the range, namely, Cantwell Glacier, the glacier at the head of Eureka Creek, and that one in which Gulkana River heads, all contribute water to two separate great drainage basins. The obvious outlet for the waters from all these glaciers is to the south, for the distance to the sea is shortest in that direction, and a high mountain range must be crossed by any northward-flowing streams. No detailed studies have been made at any of these places, but in each of the three cases the controlling conditions were probably much the same. The greater accumulation of glaciers on the south side of the range, at the time of the maximum glaciation, filled both Copper River and Susitna basins with ice to a great thickness, as has already been stated. This ice body found such outlets as were available and at least two tongues pushed northward across the Alaska Range through what are now Broad and Delta passes. These outlets of escape were probably determined by low divides created by the

[1] F. H. Moffit, "Headwater Regions of Gulkana and Susitna Rivers, Alaska," *Bull. U.S. Geol. Survey No. 498*, 1912, p. 53.

preglacial streams. Both passes were scoured deeply by glacial erosion, and when the ice retreated the low gaps were left. We do not know whether the early postglacial drainage followed the present lines or not, but as the valleys were gradually filled with glacial outwash gravels the streams flowed sometimes in one direction, sometimes in the other. Gulkana Glacier, in the fall of 1910, was observed to send most of its water into the Delta River drainage, although a small stream flowed to the Gulkana. The constant shifting of channels which takes place doubtless gives the Gulkana the greater portion of water in some years.

COPPER RIVER BASIN

Between Delta and Mentasta passes there is a large number of glaciers draining by various tributary streams into Copper River. As the mountains are here all less than 10,000 feet in elevation, the glaciers are in general smaller than those of the higher mountains west of the Delta. Mendenhall, who visited these glaciers in 1902, says:[1]

> The most conspicuous of them is the one in which Gakona River rises (Fig. 7). It is perhaps 12 miles long and expands near its foot to a width of 3 miles. This lower portion is a rough, pinnacled mass of ice which rises several hundred feet above the valley floor on either side, and is visible for many miles in either direction.
>
> Chistochina Glacier fills the greater part of the narrow piedmont valley north of Slate Creek and the upper Chisna. It flows east and west into branches of Chistochina River, and receives as tributaries a number of smaller glaciers which flow down from the crest of the range.

Mendenhall fails to state whether the glaciers at the time of his visit gave evidence of recent retreat or advance.

GLACIO-FLUVIAL DEPOSITS AND MORAINES

Great areas in the Copper River basin are covered with deposits which are directly or indirectly of glacial origin. In the interstream areas these beds are composed largely of glacial till. Along the stream courses there are extensive deposits of glacial outwash gravels. Their distribution is shown on Plate I.

[1] W. C. Mendenhall, "Geology of the Central Copper River Region, Alaska," *Prof. Paper U.S. Geol. Survey No. 41*, 1905, p. 89.

FIG. 5.—Panorama of a part of Gulkana Glacier. Photograph by F. H. Moffit, 1910

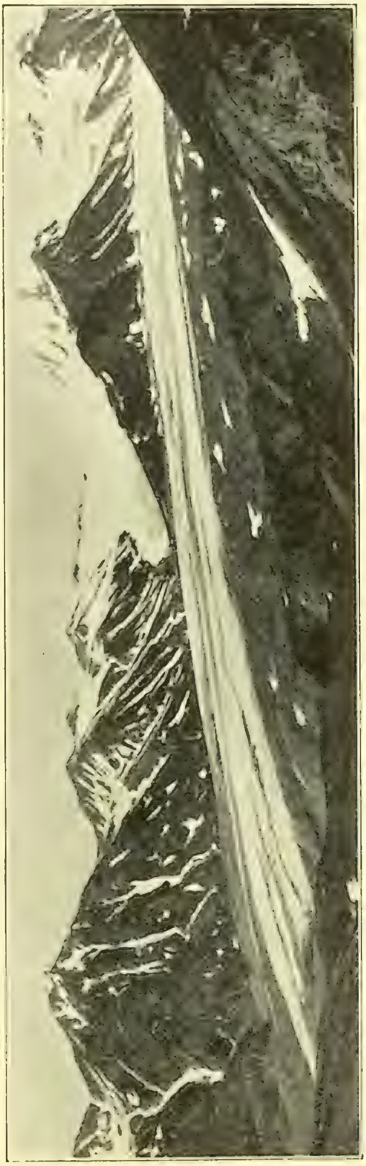

FIG. 6.—Lower end of Gulkana Glacier. This glacier sends a part of its drainage to the Pacific Ocean by way of Gulkana and Copper rivers, and the rest to Bering Sea through Delta, Tanana, and Yukon rivers. Photograph by F. H. Moffit, 1910.

TANANA AND KUSKOKWIM BASINS

The Tanana slope of the Alaska Range, between Mentasta Pass and Delta River Valley, is unsurveyed, and little is known of the glaciers there beyond the fact that as seen from Tanana River there appears to be no great development of snow fields in these mountains, and it is likely that the glaciers are smaller than on the south slope, as in other parts of the range.

FIG. 7.—Gakona Glacier from below. The vegetation-covered terminal moraine indicates that the glacier is in a state of retreat. Photograph by W. C. Mendenhall, 1902.

DELTA RIVER DRAINAGE

Two large ice tongues push down toward Delta River from the east and furnish a considerable part of its waters. The uppermost of them, known as Canwell Glacier, heads opposite to Gulkana Glacier. Its upper basin is unsurveyed. The terminus pushes down to within two miles of the Delta and is heavily moraine covered. A short distance north of it another, Castner Glacier, terminates at the edge of the Delta Valley. Its front is somewhat expanded forming a bulb-

shaped lobe, and is covered with morainal material upon which alder brush and other bushes have established themselves. Its melting waters emerge as a large stream from beneath the ice (Fig. 8).

FIG. 8.—The emergence of a glacial stream from beneath Castner Glacier, 1910

West of Delta River the mountains are higher and the glaciers of larger size. One large unnamed glacier emerges from the central part of the range and terminates on the banks of Delta River. It is known to have a length of more than 20 miles, and averages more than a mile in width. Its terminal end is heavily covered with débris, and terminal moraine deposits indicate that the glacier is retreating.

DELTA CREEK DRAINAGE

Delta Creek drains a part of the high group of mountains in the vicinity of Mount Hayes and heads in two important glaciers.

That one which gives rise to the main fork of the stream is 17 miles long and in places is two miles wide (Fig. 9). The lower end is moraine covered for several miles and gives evidence that it is probably in a state of retreat. East Fork of Delta Creek has its source in a glacier which descends from the slopes of Mount Hayes. While most of its waters are tributary to Delta Creek, a small lobe drains northwest to Little Delta River.

LITTLE DELTA RIVER DRAINAGE

East Fork of Little Delta River rises in the third large northward-flowing glacier from the mountains about Mount Hayes and Cathedral Mountain (Fig. 10). Some of its headward tributaries

FIG. 9.—Delta Creek Glacier. The high peak at the right is Mount Hayes. 1910

lie in unexplored territory, but the glacier is known to be more than 15 miles long and its main lobe is over $1\frac{1}{2}$ miles wide. The foot is moraine covered and ends in a thin edge. Outstanding moraine ridges show the glacier to be retreating.

OTHER GLACIERS IN UNSURVEYED AREAS

To the west of the East Fork of Little Delta River there are a number of streams, notably West Fork of Little Delta River, Wood River, Yanert Fork of Nenana River, and Toklat River which head in unsurveyed areas, but which are known from the character of their waters and from the reports of prospectors to head in glaciers. In most of this region the mountains are lower than to either the east or the west, and it is probable that the glaciers are of comparatively small size.

KANTISHNA AND KUSKOKWIM DRAINAGE

The glaciers on the northwest slope of the range, in its highest part, drain either by Kantishna River to the Tanana or into the Kuskokwim. Only a narrow belt along the base of the mountains has been surveyed and information concerning the glaciers is meager. Of them Brooks[1] says:

All the largest northward-flowing glaciers of the Alaska Range rise on the slopes of Mount McKinley and Mount Foraker. Of these the largest are the Herron, having its source in the neve fields of Mount Foraker; the Peters, which encircles the northwest end of Mount McKinley, and the Muldrow, whose front is about 15 miles northeast of Mount McKinley, and whose source

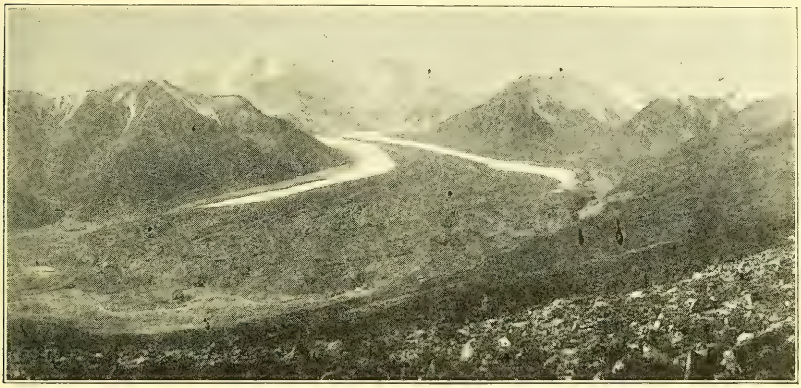

FIG. 10.—Glacier at the head of East Fork of Little Delta River. The high peak in the center is Cathedral Mountain. Photograph by J. W. Bagley, 1910.

is in the unsurveyed heart of the range. The fronts of all these glaciers for a distance of one-fourth to one-half a mile are deeply buried in rock débris.

Along the crest line there are numerous smaller glaciers, including many of the hanging type. Both slopes of Mount McKinley and Mount Foraker are ice covered. . . . . The glaciers that came under the observation of the writer all appeared to be receding rapidly. There is, however, little proof of the rate of recession. Spruce trees about 6 inches in diameter were seen in the old path of the Muldrow Glacier about 5 miles from the present ice front. If the age of these trees is estimated at fifty years, this fact, so far as it goes, indicates an average annual recession of about one-tenth of a mile.

QUATERNARY DEPOSITS IN THE TANANA AND KUSKOKWIM BASINS

Since the higher mountains are still in the glacial period, and since moraines and outwash materials are now being, and have

[1] A. H. Brooks, "The Mt. McKinley Region, Alaska," *Prof. Paper U.S. Geol. Survey No. 70*, 1911, pp. 125–26.

been continuously deposited since Pleistocene times, it is impossible to make a sharp separation between the deposits which are directly or indirectly of glacial origin, and those which are now being formed by the streams. Glacial waters form such an important element in the drainage of both Kuskokwim and Tanana rivers that all the deposits of these two great rivers might be considered to be of glacio-fluvial origin. On the accompanying map (Plate I) all the Quaternary deposits, including morainal material, glacial outwash, terrace gravels, and the present stream deposits, are mapped in a single pattern, and are indicated only within the area which is believed to have been covered by glacial ice. Beyond the northern limit of glaciation, as mapped, the broad lowlands of both Tanana and Kuskokwim rivers are covered with Quaternary deposits which probably attain great thickness. It should be remembered that northwest of Mount McKinley the line along which the northern limit of glaciation is mapped, and much of the area shown as covered with Quaternary deposits, has not been critically studied, and the mapping as given here has only a tentative value.

SUMMARY

The higher portions of the Alaska Range are still in the glacial period, the difference between the present glaciation and the former more extensive glaciation being one of degree and not of kind. The present mountain glaciers are all of the valley-glacier type, no large, unbroken ice caps being known. Even at the time of the maximum glaciation the higher peaks and ridges probably projected above the ice mass, and the mountain glaciers even then were valley glaciers. In earlier times the glaciers protruded from their mountain valleys and coalesced into piedmont glaciers. On the south side of the range these attained great size, filling both Copper and Susitna basins and extending southward along the valleys of these rivers to the Pacific Ocean, and having a thickness measured in thousands of feet. Ice from these basins pushed northward across the Alaska Range through Delta and Broad passes, and probably also through Mentasta Pass. On the north side of the range the former glaciers were also of much greater

size than the present ones, but the ice fields there were never equally extensive with those on the south. The present distribution of glaciers shows the same contrast between those on opposite sides of the range, but the discrepancy is not so great now as formerly. In the vicinity of Mount Hayes this difference is least well marked, the ice tongues draining to the Tanana being only slightly smaller than those at the head of the Susitna. None of the earlier glaciers north of Mount Hayes reached more than 30 miles farther than the present ice edge, while south of this mountain the glaciers extended more than 200 miles beyond the present terminations. From the facts available in regard to this point, the glaciers of the Alaska Range seem in general to be in a state of retreat. Several large glaciers southeast of Mount McKinley are exceptions to this rule and are either advancing or have remained about stationary for a time sufficiently long to allow good-sized trees to grow in their paths.

The Alaska Range offers a wide range of types and a great number of examples of the many forms of valley glaciers, and offers an attractive and practically untouched field for the student of glacial phenomena.

SOME SMALL NATURAL BRIDGES IN EASTERN WYOMING[1]

V. H. BARNETT

Natural bridges have been described at length by Mr. Herdman F. Cleland[2] in a paper read before the Geological Society of America, December 29, 1909, and less extensively from time to time by Walcott, Cummings, Pogue, and others.[3]

Small bridges observed by D. E. Winchester and the writer, in Weston and Converse counties, Wyoming, seem to justify a brief description, as they belong to a little different class from any discussed by these writers. Of the different types enumerated the bridges in Wyoming more nearly resemble the one formed by a petrified log spanning a ravine in the petrified forest of Arizona, described by Mr. Cleland,[4] but differ from it in that they owe their existence to indurated masses or concretions instead of to a petrified log as in the case cited by Mr. Cleland.

The beds of the Fort Union and Lance formations of this district (eastern Wyoming) contain a predominance of soft sandstone and sandy shale. Almost everywhere in the sandstone are inclusions of concretions and indurated masses. They present a great variety of forms. Some are nearly perfect spheres from the size of a marble to eighteen or twenty inches in diameter; others are more irregular and vary from the shape of a log to very irregular masses sometimes several hundred feet in length. These larger

[1] Published by permission of the Director of the U.S. Geological Survey.

[2] Cleland, H. F., *Bull. Geol. Soc. Am.*, XXI (1910), pp. 313–38, pls. 18–38.

[3] Charles D. Walcott, "The Natural Bridge of Virginia," *Nat. Geog. Mag.*, V (1893), pp. 59–62; Herdman F. Cleland, "The Formation of Natural Bridges," *Am. Jour. Sci.*, 4th ser., XX (1905), pp. 119–24, 3 figs.; V. H. Barnett, "A Natural Bridge Due to Stream-Meandering," *Jour. Geol.*, XV (1908), pp. 73–75, 2 figs.; Byron, Cummings, "The Great Natural Bridges of Utah," *Nat. Geog. Mag.*, XXI (1910), pp. 157–67; Joseph E. Pogue, "The Great Rainbow Natural Bridge of Southern Utah," *Ibid.*, XXII (1911), pp. 1048–56, 6 figs.

[4] *Loc. cit.*

indurated masses when they lie in the way of a receding gulch sometimes result in natural bridges. Their origin is easily explained. As the gulch receded the water first exposed the indurated mass, then a waterfall was formed and undercutting commenced. This process soon removed the softer material until the water flowed under the harder mass and a natural bridge was formed. In Fig. 1, a loglike concretion is seen at the very head of a gulch, which has recently been undercut. The diameter of the concretion is about three feet and its length is about ten feet. In this case

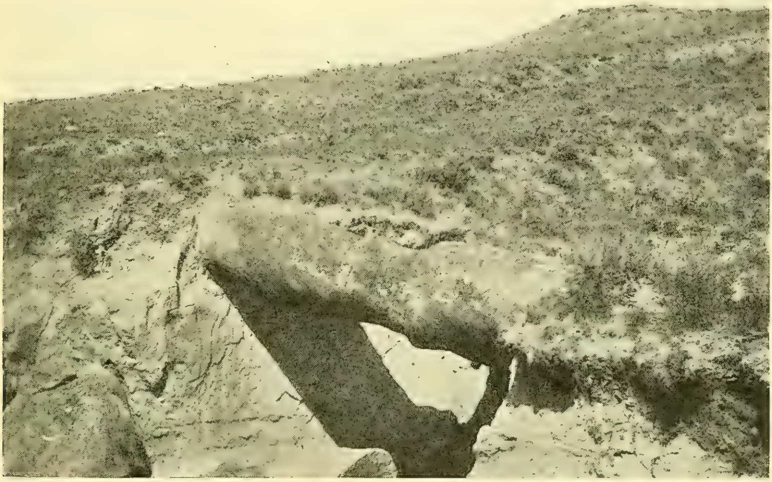

FIG. 1.—Loglike concretion occurring in friable sandstone of Lance formation about eight miles south of Moorcroft, Wyo.

one could step from the bridge to the bank at the head of the gulch.

Fig. 2 represents a bridge spanning a ravine 30 feet wide and 12 feet deep. The loglike concretion is 5 feet wide by about 3 feet thick and is quite uniform throughout its length. It is flat on top and sufficiently firm to support a saddle-horse, as shown in the picture. The third case (Fig. 3) shows an indurated sandstone mass less regular in outline than either of the others. This one was visited by Mr. Winchester who states that the bridge is about 16 feet long and 4 feet wide on top. The thickness of the indurated

mass spanning the gulch is about four feet at one end and two feet at the other. As may be seen by the illustration it is about ten feet

FIG. 2.—A natural bridge in the Lance formation at head of a gulch on the divide between Cow and Lightning creeks, Wyo.

FIG. 3.—Natural bridge in the Fort Union formation about 30 miles northeast of Douglas, Wyo. (Photograph by D. E. Winchester.)

above the bottom of the gulch. This bridge is apparently more stable than either of the others cited. From the appearance of the

bed of the gulch erosion is slight at the present time, so that it will probably be a very long time before the ends of the bridge are undercut sufficiently to cause either end to tumble down.

The formation of natural bridges of this type is easily understood but the origin of the indurated masses whose existence makes the bridges possible is not so readily explained. The indurated masses appear to fall into two classes, the one taking a more or less regular and uniform outline (seen in Fig. 1) and the other a sort of irregular lense of the rock (Figs. 2 and 3). In the first case it is probable that a part of the mass has been replaced by chemical solution, while in the second case the cementing material is already contained in the mass and only requires time to become indurated. Todd[1] in describing similar occurrences in rocks of this age in South Dakota states that they probably mark ancient shore lines. It is in fact quite common to find the indurated masses at one level along an outcrop for several miles and it is not improbable that the waves of one storm, for instance, might throw together along a shore line or in a stream channel materials which would contain in themselves constituents that afterward become indurated.

Barnum Brown[2] has stated in a discussion of the "Hell Creek beds" (Lance formation) of Montana that "it is not an infrequent sight to see several parallel concretions, circular in cross-section and a hundred feet in length, like fallen trees." He says further that "they are not, however, true concretions but centers of solidification. Cross-bedding in the surrounding sandstone is frequently carried through the concretions line for line." These indurated masses are invariably darker color than the more friable surrounding sandstones. Probably they were originally about the same color as the friable material, but either percolating waters have leached the iron out of the friable sandstone or else more rapid erosion prevents oxidation.

[1] J. E. Todd, *Am. Geol.*, XVII (1896), pp. 347–49.

[2] Barnum Brown, *Am. Mus. Nat. Hist. Bull.*, XXIII (1907), pp. 829–32.

ROCK-CUT SURFACES IN THE DESERT RANGES[1]

SIDNEY PAIGE

In an article entitled "The Geographical Cycle in an Arid Climate"[2] William M. Davis has presented a physiographic analysis of the ultimate results of erosion in an arid region. His conclusions are based partly on the work of Passarge and others and partly upon his own deductions. The system erected is in its larger features so complete that those who follow in interpreting particular physiographic products need only assign such features to their proper place in the larger system already established. That the following conclusions, therefore, were reached independently and seem to fit perfectly with the system outlined by Davis is an additional corroboration of the soundness of his deductions, and the excuse for their publication must rest upon the wish expressed by Davis "that the scheme of the arid cycle may lead to the detection of many facts concerning the evolution of land forms in desert regions that have thus far escaped notice."

G. K. Gilbert[3] stated in describing the Basin Range system of the West: "Between them [the ranges] are valleys floored by the detritus from the mountains which conceals their depth and leaves to the imagination to picture the full proportions of ranges of which the crests alone are visible, while the bases are buried beneath the débris from the summits." It is with the processes by which gravel sheets engulf mountain masses and with certain erosional features associated with such accumulations that the following notes have to do. An explanation is sought for a number of rock-cut benches or surfaces, occurring at the edges of Quaternary gravel sheets in the Silver City quadrangle, New Mexico. The facts will be presented first; what is believed to be an analogous

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] *Journal of Geology*, XIII, No. 5, July-August, 1905.

[3] *Report upon Geographic and Geologic Surveys West of the 100th Meridian in Charge of Lieutenant George William Wheeler*, Vol. III, p. 22.

case will be described next; and certain conclusions more or less hypothetical will be stated last.

Well-marked though dissected rock-cut benches occur in a number of areas within the Silver City quadrangle. Their relations to the highlands, out of which they have been carved, and to

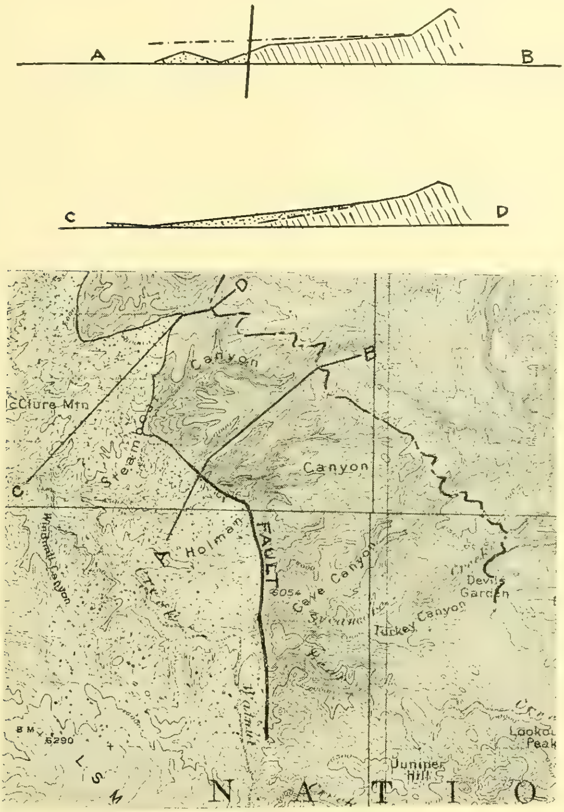

FIG. 1.—Vertical scale double the horizontal. 1 square = 1 mile

the gravel deposits, to which they contributed material, are shown in Figs. 1, 2, 3, and 4. The shaded portions show the areas in which the rock-cut dissected surfaces are found. Dotted areas indicated gravel. The most important features of these benches are: first, that they slope gently upward from the edge of the gravel with a profile concave upward and terminate abruptly against a mountain

flank of considerable steepness; second, that they present a remarkable evenness of surface, when viewed from a sufficient distance to reduce the prominence of recent dissection; and third, that they truncate rock structure without any decided evidence of selection.

As indicated in Fig. 1, the boundary between the gravel and the bench of hard rock may be divided into two parts; one where erosion has revealed a depositional unconformity, the other where faulting has disturbed this normal relation. The slope of the bench

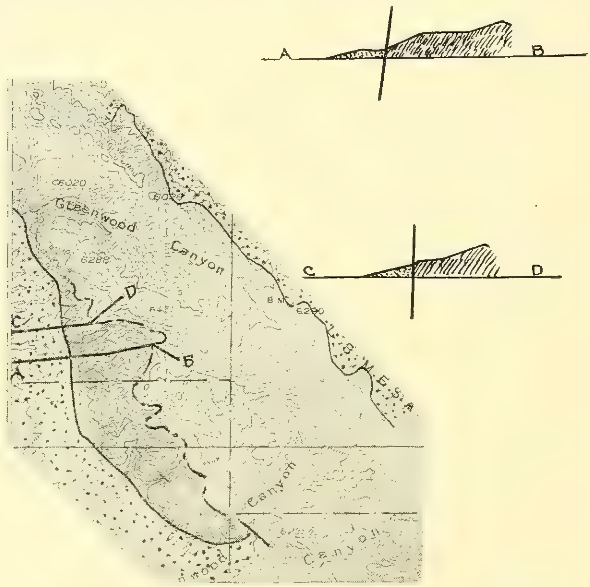

FIG. 2.—Vertical scale double the horizontal. 1 square = 1 mile

in continuous with the slope of the gravel sheet, and is astonishingly regular from the edge of the gravel to the mountain front. Notable is the irregular depositional boundary in the northern portion where the gravel rises gently upon the bench nearly to the foot of the mountain scarp; notable also the straight boundary where faulting has altered this relation.

It seems that the conditions here are peculiarly fortunate and diagnostic. If the faulting had not occurred, it is doubtful whether the bench would have been exposed. Even the northwestern portion would probably have been more completely covered. As it

happens, the gravel sheet is shown reaching almost to the mountain core upon a sloping rock-cut bench. That the bench contributed to the sheet and that the sheet gradually crept mountainward over the bench seems plausible. A fault has raised the bench,

FIG. 3.—Vertical scale double the horizontal. 1 square = 1 mile

which, by virtue of its elevated position, has been stripped by erosion of a considerable part of the gravel deposit from the area above the fault line. Patches remaining are taken to show that the bench was formerly gravel capped throughout.

In Fig. 2 the northeast and southwest sides of a low mountain range are shown with the Pleistocene gravel boundaries. Attention is called first to the proximity of the northeastern boundary to the crest line of the range, second, to the relatively straight boundary of the western gravels along whose entire course there is believed to exist a fault. The bench here exposed (though severely dissected by sharp canyons) is interpreted as the old floor upon which gravel once lay, and here again the gravel has been removed because of its superior elevation. An interesting point is the narrowness of the mountain remnant if, in imagination, we restore the gravel to the bench. It shows clearly how nearly the mountain range escaped destruction.

Fig. 3 shows a mountain core and gravel-free rock bench which slopes outward from the mountains and passes beneath a sheet of gravel. The bench is a striking physiographic feature. In this case special attention is called to the southeastern portion where the gravel has been cleanly swept from a portion of the bench. Although straight boundaries between gravel-covered and gravel-free portions of the bench are not observed, there are geologic reasons for believing that there has been uplift, a movement sufficient to initiate removal of the gravel sheet and dissection of the bench.

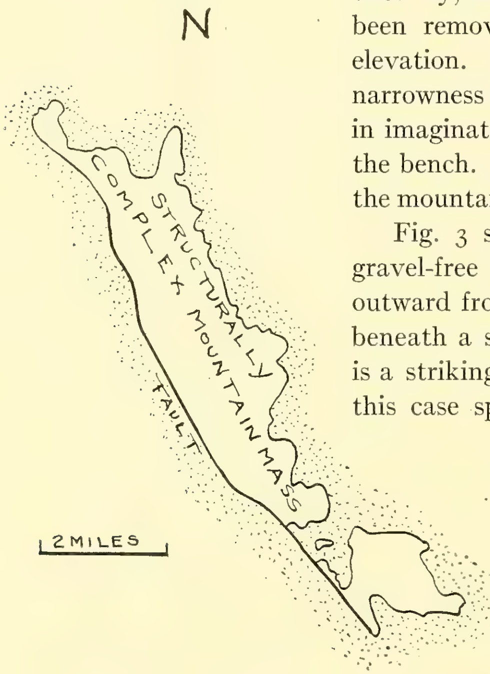

FIG. 4

Fig. 4 shows a mountain mass with its surrounding gravel sheet. Note the straight fault contact on the southeastern side. The figure is somewhat analogous to Fig. 2 but the remains of any bench that may have existed is nearly or quite obliterated by recent cutting. The figure serves, however, to show, because of the fault,

that the original remnant of the mountain left by the gravel encroachment was probably narrower even than at present.

It should be stated that the gravels here referred to are the borders of very extensive desert deposits, stretching for miles to to the south and west and are, or have been, the encroaching tongues of the great sheets; the tentacles, so to speak, by which gravel accumulation incorporates a mountain mass.

The scene for a moment may now well be shifted to "the broad expanse of plain and mountain in southwestern Arizona and western Sonora (Mexico), stretching from the Sierra Madre to the Gulf of California and lying between Gila and Yaqui rivers."[1]

> At first sight the Sonoran district appears to be one of half-buried mountains, with broad alluvial plains rising far up their flanks, and so strong is this impression on one fresh from humid lands that he finds it difficult to trust his senses when he perceives that much of the valley-plain area is not alluvium, but planed rock similar to or identical with that constituting the mountains. To the student of geomorphy this is the striking characteristic of the Sonoran region—the mountains rise from the plains, but both mountain and plain (in large part) are carved out of the same rocks. The valley interiors and the lower lowlands are, indeed, built of torrent-laid débris, yet most of the valley area carries but a veneer of alluvium, so thin that it may be shifted by a single great storm. Classed by surface, one-fifth of the area of the Sonoran district, outside of the Sierra and its foothills, is mountainous, four-fifths plain; but of the plain something like one-half, or two-fifths of the entire area, is planed rock, leaving only a like fraction of thick alluvium.

Thus is clearly set forth by Dr. W. J. McGee the product of a long cycle of erosion.

A short digression is necessary here in order to define the term sheet flood, the force of which agent is of importance in the present discussion. In the words of W. J. McGee,

> Under certain conditions, sand-laden water flowing over an erodable plain tends at first to divide into parallel streams like those of pure water on an indestructible surface, yet, since the streams formed in this way at once begin to scour and overload themselves and thus check their own flow, this tendency is soon counteracted and the water is distributed again; so that the ultimate tendency is toward movement in a more or less uniform film or sheet.

[1] McGee, W. J., "Sheet Flood Erosion," *Bull. Geol. Soc. Amer.*, VIII, February 13, 1897, pp. 87–112.

Regarding the efficacy of sheet floods to erode the land surface W. J. McGee says:[1]

> The inference from the character of the sheet flood is consonant with the necessary inference from the character of the base level surface. Over dozens or scores of square miles in carefully examined localities, hard rocks like those of the mountains, and with no sign of decomposition, are planed almost as smooth as the subsoil by the plowshare, with nothing either in configuration or in covering to indicate that streams have flowed over them, and extended consideration has yielded no other suggestion as to the eroding agent than that found also in analogy with the observed sheet flood.

Thus in unequivocal terms the rock-cut plains are assigned to an origin by sheet-flood erosion. The question naturally arises in the mind of the reader, Was there a stage in the past history of the region during which such plains might have been formed by a process approaching in kind that of peneplanation? Again quoting W. J. McGee:[2]

> The fourth inference is that the massif [he refers here to an uplifted folded area] produced in this way stood at moderate altitude for a long period including approximately the Eocene and the earlier half of the Miocene, that a large part of its volume was degraded; that the surface was planed to an *approximate base level*,[3] relieved by ridges and masses of the monadnock and catoctin types, usually of harder layers but sometimes marking broad divides, and that during this vast period the drainage basins were outlined and developed. It is deemed probable that during much or all of this period the precipitation was greater than now, so that the district throughout was one of degradation and so that the drainage basins were of the normal dendritic type veined by rivers occupying broad yet essentially V-shaped valleys; and it is considered probable also that the basin-limiting Sierras were less rugged than now.

The meaning of the above paragraph is a little ambiguous—the reference to "approximate base level" does not fit in with "rivers occupying broad yet essentially V-shaped valleys." One cannot reach a definite conclusion, therefore, as to whether the rock-planed surfaces, referred to above, were dependent upon this stage for their beginnings. But considering the language used in describing the rock-planation, one is inclined to infer that W. J. McGee regards sheet-flood erosions as the primary process in such planation.

The foregoing description of the Sonoran benches, it seems to the writer, applies to the rock-cut surfaces of the Silver City region,

[1] *Op. cit.*, p. 108. [2] *Op. cit.*, p. 95.

[3] *Underscoring* by the writer of this paper.

provided the plane surface now scarred by recent dissection be assumed restored. Post-Quaternary faulting (probably an effect of more widespread uplift than is indicated by relative movements of blocks) is a sufficient cause for the dissection which has occurred.

A hypothesis to explain the features described above may now be presented. The intention is not to follow a process throughout all its possible variations, but to suggest an idea which may serve as a nucleus for future elaboration. All the processes by which rock-cut benches may be formed need not be enumerated. The facts in this case point obviously to the encroachment of an accumulating gravel sheet upon a highland area. The end result now achieved may perhaps be attained as follows.

An area (of which the Basin Range system is an example) may be so warped by regional uplift that inclosed basins are formed. A climate is postulated of such aridity that permanent lakes will not rise to such altitudes as to overflow the rims of the inclosed basins. Such basins are favorable for the rapid sub-aerial accumulation of detrital matter.

Active erosion within this system now becomes regulated by an all important factor: *progressive burial by alluviation of low-lying areas.* It is conceived that a central portion retains its original topographic sculpture because of complete oversweep of débris. Each succeeding portion of topography before it is buried will have been more reduced, will have been more softened in that it has suffered a longer period of exposure than the portion immediately preceding it.

The rising edge of the gravel sheet acts as an effective control below which erosion cannot take place. The result is unavoidable if *the time factor* and *the factor of area* are sufficiently large. *A process tending toward leveling with respect to the gravel sheet will proceed.* But the gravel sheet has been gradually rising; therefore, *the leveled surface is a sloping plain thinly veneered with gravel.*

A second process, it is believed, plays an important part in this result. The feature which leads to the recognition of the process is the abrupt change of gradient at the mountainward border of the rock-cut plain. A consideration of the character of the stream channels which debouch upon the rock-cut plain may give a clue

to the origin of this oversteepening of topographic gradient. Aggrading streams flow out upon fans and fans have a cross-section concave upward. Such a cross-section implies that from time to time the stream will flow against the mountain wall and initiate lateral cutting. It may be argued in opposition to this view that it will build up here as elsewhere and prevent any persistent lateral cutting at a definite level. This objection may be answered by pointing out that a desert level of great expanse is a feature of great stability, far more permanent than the local filling at the side of a fan. This filling may be swept out and renewed many times before the general level of the desert is raised an appreciable amount by accumulation. This process then, viz., lateral cutting, combined with that outlined in the preceding paragraph, seems to account for all the conditions that need explanation. Both must have worked from the beginning of the cycle.

CONCLUSIONS

The considerations which have been outlined above suggest the following tentative conclusions: (*a*) Processes of erosion within an inclosed basin system in an arid climate tend ultimately to produce surfaces of very low relief about the borders of the gravel sheet which accumulate within the basin. (*b*) The gradual rising of the gravel filling implies an equally gradual rising of the local base level. (*c*) The surface resulting from such a shifting system tends ultimately to take the form of a sloping planated surface, most perfect at its mountainward side and progressively more irregular valleyward beneath the gravel cover. (*d*) Interstream erosion, lateral cutting at edges of accumulating fans, and progressive burial of low-lying areas are the factors which govern the formation of the rock-cut surface. (*e*) The abnormally steep mountain flank against which the rock-cut plain abuts is considered the normal product of the three processes mentioned above. (*f*) Sheet-flood erosion is considered a *result* of the rock-cut plains and not a *cause* of the plains as hypothecated by W. J. McGee. (*g*) The old planated suıfaces near Silver City, though now dissected because of readjustments of drainage due to faulting, are regarded as examples of the type described in the Sonoran district.

SPECULATIONS REGARDING THE GENESIS OF THE DIAMOND. II

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Since writing the paper with the above title that appeared in the October-November, 1911, number of this journal Fersmann and Goldsmidt's monograph[1] on the crystalline form of the diamond has come to hand and its perusal has suggested some additional observations on the subject.

From the genetic point of view the most important deduction drawn by the authors from their epoch-making studies is stated on p. vii of the Introduction in the following terms: *All the diamond crystals known to us have been formed suspended in a molten mother-liquid* (*magma*). Since the present paper is of a speculative nature, I venture to restate, provisionally, this law as follows: *Diamond crystals have been formed suspended in a medium sufficiently mobile, or susceptible to solution* (*replacement*), *to permit their free, all-round development.* The most essential difference between the two forms of statement is the elimination in the latter of preconceived ideas regarding the physical condition of the enclosing rock at the moment of the crystallization of the mineral.

Another important deduction from the studies of Fersmann and Goldsmidt is the extreme delicacy of the saturation point for carbon of the solution from which the material of the diamond crystals was derived, from which it resulted that growth (due to supersaturation) and reabsorbtion (due to incomplete saturation) alternated in the formation period of the great majority of the individuals in a way that thus far has not been recorded as so nearly universal for any other mineral species.[2]

[1] *Der Diamant,* Heidelberg, 1911.

[2] My examination of numerous heavy residues containing zircon and monazite from granites and gneisses shows that these minerals are more frequently rounded from reabsorption than sharp-cut. The same remark can be made regarding the magnetite and ilmenite grains that occur in so many eruptive rocks.

In a recent article Irving[1] has discussed the formation of *complete* crystals in rock masses. Those that are of primary origin in igneous rocks were, naturally, formed in a magma that was mobile through fusion, while those of secondary origin are attributed to replacement. In sedimentary or other rocks already consolidated, space for such crystals could, according to Irving, only be gained through displacement of granules of the enclosing rock by virtue of the force of crystalline growth, or through the removal by solution of such molecules of the rock as occupied the space to be taken up by the crystal in process of formation.

The minerals mentioned by Irving as having had their lodging-place prepared by solution represent sulphides (pyrite, galena), carbonates (siderite), fluorides (fluorite), and boron-bearing silicates (tourmaline), from which it may be inferred that the requisite solvent power is an attribute of the so-called mineralizing agents: sulphur, carbon in some one or more of its gaseous forms, fluorine, and boron.

No precise statement regarding the character of the molds left by the dislodgement of diamond crystals from their parent-rock, kimberlite, is at hand, but judging from the current hypotheses (formed in place or floated up from some pre-existent rock), these should be as sharp-cut and perfect as those of the above-mentioned replacement minerals. Such perfect molding occurs with minerals formed in mobile (molten) media, and in the case of the diamond no other hypothesis seems to have ever been considered, but with our present scanty knowledge of the obscure subject of the genesis of that mineral the hypothesis that it may be due to replacement cannot be lightly put aside.

The studies of Beck[2] and Bonney[3] on the so-called eclogite nodules from the Newlands mine offer some support to this last hypothesis. A number of these were examined by both authors, but apparently only a single diamond-bearing one was ever found,

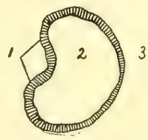
[1] "Replacement Ore Bodies and the Criteria for Their Recognition," *Economic Geology*, October-November, 1911.

[2] "Untersuchungen über einige südafrikanische Diamantenlagerstätten," *Zeit. d. deutsch. geol. Gesell.*, 1907, pp. 290 f.

[3] "The Parent-Rock of the Diamond in South Africa," *Proc. Roy. Soc.*, LXV (1899), p. 229.

or at least brought to Europe. They consist essentially of diopside and garnet, the former mineral predominating in the sterile nodules and the latter in the diamond-bearing one. The small flake studied by Beck had the volume of a cube of 7–8 centimeters length of side and showed five diamonds on the fractured faces. Six more were obtained by crushing some small detached fragments, from which it was estimated that the whole flake contained some dozens of diamond crystals, and the original nodule from which it was broken (said to have been of about the size of a child's head) some hundreds. The diamonds were embedded in the diopside[1] or between this mineral and the garnet. The granules of garnet were covered with a thin dark crust similar in appearance to the well-known kelyphite rim found on this mineral in many other rocks but apparently of a somewhat different character. This crust was not reported on the garnet of the much more abundant sterile nodules, and if it occurs at all in them, it is apparently localized in certain spots that were not critically examined.

The accompanying figure reproduced from Bonney shows the relation of a diamond crystal to a neighboring granule of garnet covered with its characteristic crust, which is said to extend also into cracks in the garnet.



Garnet and diamond (diagrammatic, nearly twice natural size): (1) Diamond, (2) garnet, (3) kelyphitic rim.

If, instead of to the diamond, this figure referred to any one of the above-mentioned replacement minerals, the following interpretation of the phenomena registered in it would probably be accepted by most, if not by all, mineralogists who have occupied themselves with the study of the genesis of minerals.

A dyke, or pipe, of kimberlite containing nodules (segregations) of diopside and garnet was subjected to pneumatolitic action that introduced water and carbonic acid into the rock, producing the serpentinization of a considerable part of it accompanied by the formation of calcite. Some of the included nodules (the more brittle ones containing more garnet than diopside would have been

[1] See figures in *Zeit. f. prak. Geol.*, May, 1898, p. 164.

most affected by the previous fracturing that the rock had suffered) were affected by this action, as is evidenced by the production of a crust of secondary minerals on the surface and in the cracks of the garnet and produced at its expense.[1] At a certain point on the surface of the granule here considered that was being attacked, certain ingredients contained to the point of supersaturation in the corroding solution commenced to separate out in a crystalline form, substituting the crust which at that point was being redissolved on its outer surface while its formation continued on the inner one. In front and around the growing crystal the solvent action of the solution on the garnet and the consequent formation of the crust became more active than elsewhere, thus lowering the original surface at that point and producing the bay-like indentation in which the crystal rests.

All the hypotheses thus far presented for the genesis of the diamond are difficultly reconcilable with the known geological conditions of its occurrence as summarized, so far as regards those that are most essential, in my previous paper. Friedländer[2] has demonstrated experimentally that the diamond can be produced artificially by introducing solid carbon into fused olivine without artificial pressure and at a temperature (that afforded by the oxyhydrogen blowpipe) considerably below that thought indispensable by previous experimenters.[3] We can therefore in our speculations on the subject eliminate altogether the element of pressure and, until the contrary is proven experimentally, admit hypothetically a still further extension downward of the range of temperature which, under varying conditions in other respects, will permit the crystallization of carbon in the form of diamond.

In speculating on the genesis of the diamond we can therefore put aside, at least hypothetically, the formidable ancient bugbear

[1] In this case the dissolved material was redeposited *in situ*. If we imagine that the material that, as may be presumed, was concurrently dissolved from the diopside was carried away (and perhaps with it a certain portion of redissolved garnet crust), a plausible explanation is found for the much-discussed rounded form of these nodules.

[2] "Herstellung von Diamanten in Silikaten entsprechend dem natürlichen Vorkommen im Kaplande," *Verh. d. Vereins z. Beförderung des Gewerbfleisses*, February, 1898, p. 45.

[3] A repetition of these experiments with other minerals, especially diopside and garnet, might give a very desirable addition to our knowledge of the subject.

of extraordinary pressure and heat, and thus nothing of serious importance stands in the way of a thoughtful consideration of the hypothesis here presented that the diamond is a secondary mineral crystallized out of some carbon-bearing solution that was capable of dissolving the rock (or some parts of it) in which it occurs and thus of opening space for it. This hypothesis can be easily reconciled with the geological conditions in which the diamond occurs in its parent-rock, in so far at least as these conditions are known at present. These, as set forth in my previous paper, combined with the present one, are as follows:

1. The diamond occurs in the form of isolated complete crystals closely enclosed in a rock of eruptive origin occurring in dykes and pipes and having the readily alterable minerals olivine and pyroxene as its leading essential constituents.

2. This rock, wherever diamonds have been found in it, shows evidence of having been fractured after its consolidation to such an extent as to permit a sufficiently free circulation of subterranean solutions to produce a very advanced stage of alteration in all its olivine-bearing portions, so that the only portions that remained perfectly fresh are certain unfractured pyroxene-garnet segregations free from olivine.

3. The circulating solutions introduced water (locked up in the serpentine and other secondary minerals) and carbon (locked up in the calcite) both of which were lacking in the original rock.

4. The circulating solutions attacked the garnet of the enclosed pyroxene-garnet segregations wherever these were sufficiently fractured to permit it, producing an alteration crust of secondary minerals. Unfractured segregations would naturally be attacked only on their surfaces adjacent to the more fractured and thus more permeable olivine-bearing portions of the rock, and thus their (presumably) rounded original form would be accentuated through corrosion, giving them the aspect of water-worn pebbles.

5. After (or concurrently with) the alteration of the garnet, carbon crystallized in the form of diamond adjacent to the secondary crust formed on the former mineral, and also, as Beck demonstrated in his study of the diamond-bearing nodule from the Newlands mine, in the form of graphite.

The conditions above enumerated are, in their most essential particulars, strikingly similar to those under which the mineralization, with auriferous sulphides, took place in the Passagem lode, as set forth in my recent paper in the *American Journal of Science* (September, 1911), in which, however, no mention was made of two circumstances of certain importance for the present discussion. These are: (1) large and ideally perfect crystals of arsenopyrite occur in certain portions of the hanging wall under conditions corresponding exactly to the cases of replacement cited by Irving for the sulphides pyrite and galena,[1] and (2) slick-sided planes at or near the upper side of the lode are abundantly coated with graphite which is at times segregated in lumps of the size of the fist.

Whether in this case the carbon separated out from the tourmaline-forming or the sulphide-forming solution could not be determined and is immaterial in the present discussion. Whatever its carrier may have been, it is here certain that carbon was deposited in one of its two solid mineral forms from a solution capable of dissolving portions of the rock in which it circulated, and thus of opening space for the deposit from some of the other of its mineral contents, in the form of replacement minerals such as tourmaline and arsenopyrite.

[1] The containing rock consists of a finely granular mixture of quartz, magnetic pyrite, and calcite. Where replaced, the two latter minerals disappeared while the quartz granules remained locked up in the crystals of arsenopyrite.

THE ORDER OF CRYSTALLIZATION IN IGNEOUS ROCKS

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The order of crystallization in igneous rocks is necessarily determined from the end product, the solid rock. When thin sections of the holocrystalline rocks are examined the constituent minerals show certain relations of outline to each other that give some information as to the order of crystallization. The relations of outline referred to include: the idiomorphism of one mineral against another, the indentation of one mineral by another, and the complete inclosure of one mineral by another. It is one of the objects of this paper to inquire into the conclusions that may safely be drawn from observing these relations.

Fig. 1 is a diagrammatic section of a crystal of, say, plagioclase which incloses a few crystals of another mineral, say, magnetite. Only the outer rim *A* of this crystal can be safely assumed to be of later crystallization than the magnetite. The inner portion *B* may be of later crystallization but, on the other hand, may be earlier. The fact that magnetite is situated only in the peripheral portions would make one suspect the truth of the latter possibility, but from this selfsame crystal of plagioclase an endless number of sections could be cut in which there would be no evidence of this peripheral placing of the magnetite. Some sections would contain magnetite scattered throughout, even in the most central portions. *S* of Fig. 1 indicates the direction of such a section cut in a plane normal to, or at some high angle with, the

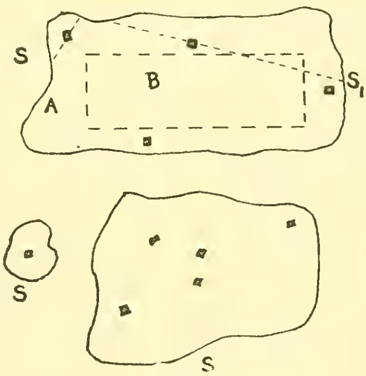

Fig. 1

plane of the page. S_1 indicates the direction of another section, cut as before, showing magnetite centrally placed in a plate of plagioclase, part of which is without doubt younger than the magnetite but part of which may be older. These sections are shown in plan in the figure. In the great variety of sections such as a rock slide commonly contains, some few would show a peripheral placing of the magnetites, but this would be regarded as mere accident in the face of the great number that showed a random placing. The conclusion as to order of crystallization would be that magnetite had crystallized before plagioclase, when as a matter of fact the greater proportion of the plagioclase might have crystallized before magnetite. Obviously the only safe conclusion that can be drawn is that *some* of the plagioclase continued to crystallize after magnetite had ceased to crystallize.

The conclusions that may be drawn from the fact that one mineral is idiomorphic against another or that one mineral indents another are qualified in a similar manner, as will be apparent from an examination of Figs. 2 and 3.

These figures represent sections of an augite crystal with a plagioclase crystal indenting it (Fig. 2) and idiomorphic against it (Fig. 3). The two cases are strictly analogous and do not require separate consideration. The relation of the minerals makes it apparent that only the outer rim A of the augite is necessarily of later crystallization than the plagioclase. The inner portion B may have crystallized later than, or simultaneous with, or earlier than, the plagioclase.

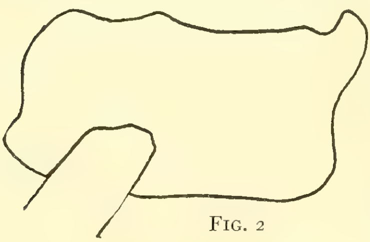

Fig. 2

The alternatives mentioned would, however, not be apparent in most other sections. S represents the direction of such a section, cut as before, and shown in plan in the figure. A natural conclusion from such sections (and a rock slide would show every variety) would be that augite crystallized after plagioclase when really the greater proportion of augite might have crystallized before. The relation of the two minerals indicates with certainty only

that augite continued to crystallize after plagioclase had ceased. The order of cessation of crystallization is the only certain information given.

In Fig. 3 but one crystal is shown idiomorphic against the augite crystal. If a great many other crystals showed the same relation to the augite, in short, if the augite crystal were interstitial to a number of other minerals, no more definite conclusion

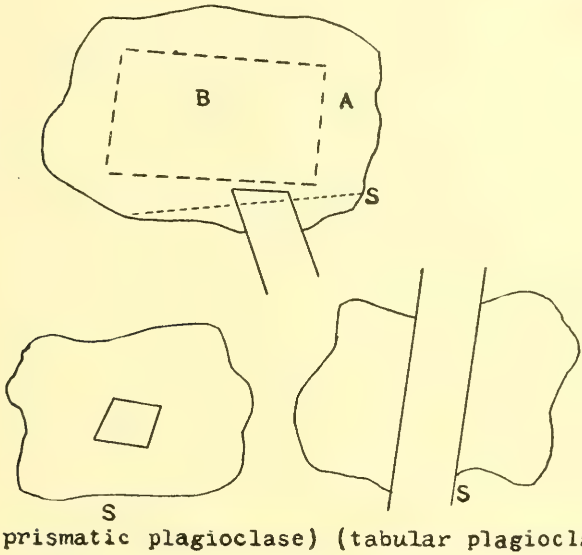

FIG. 3

than the above could be drawn. The augite crystal continued to grow after the others ceased, but it might have begun to form before the crystals to which it is interstitial.

Obviously, then, the observation of all[1] the relations of outline of a number of minerals in a section of a holocrystalline granular rock leads to a safe conclusion only as to the order in which the minerals have ceased to crystallize. Any statement of order of crystallization based on such observations should be modified to a statement merely of order of cessation of crystallization.

[1] Cf. A. Harker, *The Natural History of Igneous Rocks*, 1909, p. 179.

THEORETICAL DISCUSSION

A theoretical discussion of the crystallization of rocks can, in the present state of knowledge, lead to but few definite conclusions. It is not at all clear why there should be in any rock an *order* of cessation of crystallization. If the final crystallization is that of a eutectic mixture there should be no such order. It may be pointed out, however, that the simple eutectic results only when each constituent lowers the melting-point of every other constituent. Solid solution often brings it about that there may be a raising, and with rocks, in which, as a rule, solid solutions (mix-crystals) are very common, it cannot be said what the combination of possible "raisings" and "lowerings" may result in.

Theory, then, helps very little in making any prediction as to what ought to happen. It can, however, be safely stated that in any system the tendency of special richness in a certain constituent will be in the direction of causing that constituent to *begin* to crystallize in the early stages. A "constant order of crystallization" capable of almost universal application to all rocks, whatever the variation in mineral proportions (Rosenbusch's rules), is from this point of view out of the question. The order stated is, however, based on considerations already discussed and is really only the order of cessation of crystallization. Why a certain order should be sufficiently common to be noticeable is not apparent, but it does seem more reasonable that this should be true of the order of cessation of crystallization for various rocks than of the order of beginning of crystallization.

ORDER OF BEGINNING OF CRYSTALLIZATION

If it is admitted that the "order of crystallization" as commonly stated for any rock is merely the order of cessation of crystallization, the question arises as to whether there is no clue to be had to the order of beginning of crystallization.

In laboratory practice[1] a method of following the course of crystallization in a mixture at high temperatures is to hold the mixture in a furnace at a definite temperature for a period of time

[1] J. H. L. Vogt, *Die Silikatschmelzlösungen*, I, 106; E. S. Shepherd and G. A. Rankin, *Am. Jour. Sci.*, XXVIII (1909), 293; C. H. Desch, *Metallography*, 1910, 210.

and to quickly plunge the charge into a cool liquid which chills it instantly to a temperature at which further crystallization is permanently checked or rendered excessively rapid (metals). The examination of the chilled product reveals those constituents which had crystallized at the temperature of the furnace and by repeating at other temperatures the whole course of crystallization is followed. The method is known as the method of quenching.

The "order of crystallization" commonly stated for granite is: accessories, ferromagnesian minerals, lime-alkali feldspar, alkali feldspar, quartz. This order is determined from the outline relations of the minerals of granites which, as we have seen, can give with certainty only the order of cessation of crystallization, but for the moment it will be assumed that the order is as stated and the consequences examined. The order may be represented diagrammatically as follows.[1]

If rocks of granitic composition could be found in which crystallization had proceeded to a certain stage and had then been checked, the product should show the following characteristics. Accessories in average amount comparable with that in granites should in general be present; the most common phenocrysts, very often the only phenocrysts, should be of the ferromagnesian minerals; in rocks in which crystallization had proceeded to a considerable extent lime-alkali feldspar should accompany the ferromagnesian minerals; with more complete crystallization alkali feldspar should accompany the preceding minerals, and in a rock largely crystalline quartz should appear in company with all the above minerals.

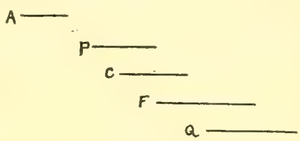

FIG. 4

In Figs. 4, 5, and 6, *A* indicates accessories, *P*, ferromagnesian minerals, *C* (calci-alkalic) lime-alkali feldspar, *F*, alkali feldspar, and *Q*, quartz.

Thousands of rocks of granitic composition are known in which crystallization has been checked at various stages (rhyolites) but they show no such peculiarities as are to be expected from the above outline. They often show phenocrysts of quartz and alkali feldspar and of these alone with the greater part of the rock still

[1] Cf. Pirsson, *Rocks and Rock Minerals*, 1909, 148.

glass. They may show phenocrysts of the ferromagnesian minerals and of lime-alkali feldspar but only in company with much alkali feldspar and quartz. Finally the accessories, instead of being almost universally present, commonly fail.

The conclusion is that the order of beginning of crystallization in granitic magma is very different from the "order of crystallization" commonly stated, that is, from the order of cessation of crystallization. Regarding the rhyolites as quenched granites the order of beginning indicated is: (quartz, alkali-feldspar); (lime-alkali feldspar, ferromagnesian minerals); accessories. (Alkali feldspar may often begin before the quartz, and ferromagnesian minerals may often begin before lime-alkali feldspar, depending upon their amounts.) If the course of crystallization is represented in diagram the result will be somewhat as follows:

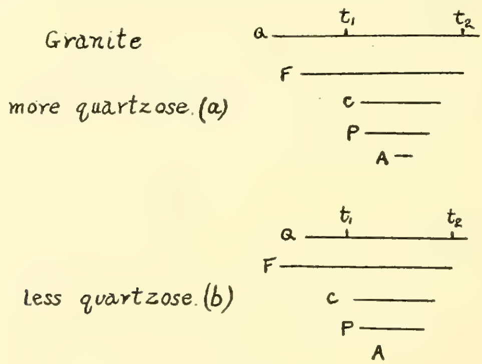

Fig. 5

The positions of the beginnings of the lines indicate the order of beginning of crystallization, and of the ends of the lines, order of cessation of crystallization. The vertical order of the lines themselves is chosen at random.

It may be objected that the crystals which a rhyolite shows often form while the rhyolite is on its way to the surface, or even after it has reached the surface, and are therefore formed under different conditions of pressure and perhaps in the presence of less mineralizers than in the case of the granite, with the result that the order of crystallization in granites is reversed in rhyolites. The likely effect of such changes of conditions is a slight displacement of equilibrium conditions, not the drastic change implied

in the above statement, but apart from the question of likelihood there is the evidence of small deep-seated bodies to be considered. These bodies crystallize under conditions comparable with those for a granite except that the rate of cooling is greater. When of granitic composition these bodies persist in showing phenocrysts of alkali feldspar and often of quartz also (Fig. 5*a*).

A study of Fig. 5 shows how such a result is possible. Quartz and alkali feldspar begin to crystallize earliest and at first the viscosity is low (relatively) so that the crystals formed grow to a considerable size. At some temperature (t_1) viscosity has increased to such a value that crystallization of quartz and alkali feldspar must proceed in the quickly cooled body by the formation of new centers. The result is a rock with phenocrysts of quartz and alkali feldspar and a matrix showing a second "generation" of quartz and alkali feldspar together with the other minerals. In the case of the granite crystallization proceeds in a similar manner and at the temperature (t_1) viscosity has reached a comparable value but the progress of crystallization is much slower and continues to take place by addition[1] to the early quartz and alkali-feldspar crystals. Lime-alkali feldspar, ferromagnesian minerals, and accessories begin and cease to crystallize as the diagram indicates; quartz and alkali-feldspar crystals continue to increase in size. Feldspar ceases to grow at t_2. At this stage quartz, like the feldspar, locally shows idiomorphism against the small amount of remaining liquid, but in the further growth of the crystals their outline is determined by the space available. The result is that the quartz crystals have an interstitial relation and there is evidence of only one "generation" of quartz, although the interior parts of the crystals formed during the earliest stages of crystallization.

The diagram affords, therefore, a systematic explanation for the textural varieties of the granite-rhyolite group as a result of different rates of cooling. The commonly stated "order of crystallization" is contradictory to the evidence of these textural varieties.

The early beginning of crystallization of quartz and feldspar is in no respect contradictory to the relations seen in thin sections of granites. It accords with the fact that Lagorio[2] failed to find

[1] A. Harker, *op. cit.*, p. 267. [2] *T.M.P.M.* (2), VIII (1887), 421–529.

the universal progressive "acidification" of the residual base of volcanic rocks which the early crystallization of ferromagnesian minerals would necessitate. Finally it may be stated that from the theoretical side the early beginning of crystallization of quartz and alkali feldspar is to be expected in a rock whose chief characteristic is richness in quartz and alkali feldspar.

It is possible, even probable, that Fig. 5 suggests too great a difference in time of cessation of crystallization of the various minerals. Certain it is that in most granites evidence of relative idiomorphism of the minerals does not leap to the eye. It must, as a rule, be carefully sought.

It may also be objected that the mode of formation of many rhyolites is of that nature which most favors supercooling with the possible result that the normal order of crystallization may suffer considerable change.[1] When, however, the quartz and feldspar phenocrysts of a rhyolite have attained considerable size they must have grown throughout a fair period of time in contact with fluid magma and therefore presumably in equilibrium with it. In short, they represent the normal early crystals.

Inductive reasoning leads one to the same conclusion. In at least some rhyolites crystallization was instituted in depth and proceeded slowly for some time before extravasation (quenching) according to the order for a granite since conditions were identical. Some quenched rocks of granitic composition should, then, show the characteristics already pointed out as consequent upon the commonly stated "order of crystallization" if this order really holds and if the observed early crystallization of quartz and feldspar is the result of supercooling or any such complication ensuant upon difference of conditions under which granites and *other* rhyolites crystallize. No quenched rocks of granitic composition which show these characteristics are, however, known to exist.

The resorption phenomena so commonly shown by the quartzes of a rhyolite might be taken as evidence that quartz may crystallize first in granitic magma, but is later resorbed and appears again only in the later stages. The gradation by insensible steps, often found in hypabyssal rocks, from vitrophyre through quartz-

[1] A. Harker, *op. cit.*, p. 213.

porphyry and granite-porphyry to a normal granite, does not bear out this conclusion, and is explicable only on the basis of the order here deduced, and a gradual change in rate of cooling. Indeed, the resorption phenomena exhibited are best explained as due to the sudden change of conditions experienced by a rhyolite, especially the relief of pressure. The specific volume of quartz is 0.377 and of "quartz glass" 0.452 at 25°. The ratio of the values of these quantities at higher temperature is probably of the same order. The great difference between these figures indicates the strong tendency that the sudden relief of pressure would have in the direction of re-solution of quartz in a magma from which it had separated.

If the crystallization of other rocks as determined by taking the evidence of plutonic and effusive types regarded as their quenched equivalents is represented in diagram, we obtain,

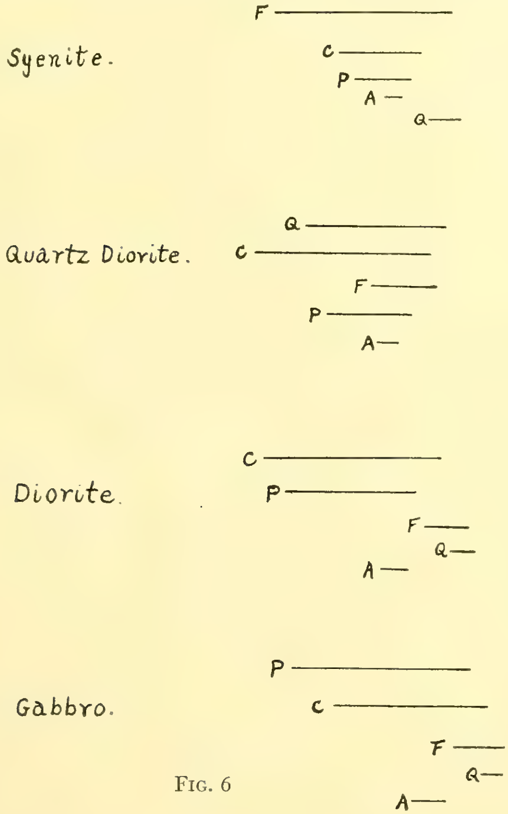

FIG. 6

For the systematic presentation of the deduced order of crystallization, the rocks (sub-alkaline) are treated in the broad types of systematic petrography. There is, of course, complete overlapping of the types and a similar gradual transition in order of beginning of crystallization. For example, the granite by increase of lime-alkali feldspar relative to alkali feldspar passes to the quartz diorite, and in the quenched equivalents alkali feldspar becomes less and less important as a mineral of early consolidation and lime-alkali feldspar more important, the result being a like passage from rhyolite to dacite. Again, the granite passes into the syenite by gradual decrease in quartz, and in the quenched equivalents quartz is represented in less and less amount as a mineral of early consolidation giving the passage from rhyolite to trachyte.

In short, there is abundant evidence throughout of the tendency of special richness in any constituent to cause the early beginning of crystallization of that constituent as theory would lead one to expect. In every case a plutonic type whose distinguishing characteristic is richness in a certain mineral, or pair of minerals, has for its equivalent effusive type a rock whose chief characteristic is the appearance of this constituent or pair of constituents as minerals of early consolidation.

It is hard to conceive a reconciliation of these well-known facts with the statement of any approximately constant "order of crystallization" on the basis of which accessories, ferromagnesian minerals, and lime-alkali feldspar should always be the minerals of early crystallization.

The broad generalization which is necessary when any type is represented by a single diagram is perhaps likely to lead to some misunderstanding. In the gabbro diagram, for example, the ferromagnesian minerals are represented as beginning first, but this must be regarded as true only for the more femic gabbros. In a gabbro approaching anorthosite, plagioclase undoubtedly begins to crystallize considerably before the ferromagnesian minerals. The difficulty is inherent in the breadth of the types.

The chief desire has not been to establish definitely the course of crystallization for all rocks referable to a given type, but to

indicate it for the average rock of any type in order that emphasis may be placed upon the importance of the effusive types as evidence of the order of beginning of crystallization and upon the distinction between order of beginning of crystallization and commonly stated "order of crystallization" (order of cessation of crystallization).

CONSEQUENCE UPON THEORIES OF DIFFERENTIATION

Variation in composition in different parts of a single rock body, or in closely associated separate bodies, is usually discussed in terms of order of crystallization of the constituent minerals. In nearly all cases the constant order of crystallization of Rosenbusch is assumed, whatever the composition of the magma treated. For example, the more femic upper portions of a granitic batholith that are so often observed have been explained as due to the early crystallization of ferromagnesian minerals at the cool contact and the continued diffusion in that direction of femic material, the result being an enrichment near the contact in ferromagnesian minerals. Apart from the question as to whether diffusion could take place and whether it would be better to appeal to convection as the mechanism of transfer, there is the fundamental question of the truth of the assumption that the ferromagnesian minerals crystallize early in granites. If it is recognized that quartz and feldspar are the minerals of early crystallization in granitic magma, the explanation is out of the question. Possibly early crystals of quartz and feldspar settled out of the contact portion.

A discussion of differentiation is not, however, intended here, and the above suggestion is made merely to show the extent to which views on differentiation may be altered by a recognition of the distinction between order of beginning of crystallization and order of cessation of crystallization (commonly stated "order of crystallization").

SUMMARY

1. The criteria for the determination of "order of crystallization" of rock minerals as applied in thin sections are discussed and it is shown that only order of cessation of crystallization can be so determined.

2. The order of beginning of crystallization is shown in the effusive types, which may be regarded as the "quenched" equivalents of plutonic types.

3. Taking the evidence of both the plutonic and effusive types, diagrams are given indicating the course of crystallization in granite, syenite, quartz diorite, diorite, and gabbro.

4. Certain consequences upon theories of differentiation are pointed out.

The writer is indebted to Professor J. P. Iddings for helpful suggestions.

Petrological Abstracts and Reviews

Berkey, Charles P. *Geology of the New York City Aqueduct.* N.Y. State Museum, Bull. 146, 1911. Pp. 283, figs. 39, pl. 38.

"Studies in Applied Geology" is the alternative title of this rather unusual work; a caption happier, and far more suggestive than that appearing on the cover of the book, for the value of the data gathered concerning the geology of this region, while great as a matter of record, is still entirely subordinate to the interest accruing from the statement of the methods used by the author in the solution of the numerous problems propounded to him as the consulting geologist of the New York Board of Water Supply. Probably in no previous engineering enterprise has such weight been placed upon the testimony of the geologist, and certainly in few has he been called upon to accumulate facts sufficient to enable him to forecast geological conditions with great accuracy over such a large area.

The author has wisely refrained from making his report a mere catalogue of the facts ascertained. "It is one of the most cherished wishes of the writer of this bulletin that some of the problems may be presented in such a manner as to serve a distinct educational purpose." To this end the problems are developed in the text nearly as they arose in the field—the data are given, with the particular information sought by the engineers; then follows the line of reasoning, and the conclusions reached; and finally the actual state of affairs, as shown by further exploration, is recorded.

The aqueduct, now in course of construction, is designed to carry over half a billion gallons daily, from the Ashokan Reservoir in the Catskill Mountains, to the Hill View Reservoir, just outside of the city, and includes 92.5 miles of aqueduct, with 10 dams; and 18 miles of additional tunnel, with 16 miles more of delivery pipe line in New York City itself.

From the Catskills south to the Highlands the territory under consideration is underlain by Paleozoic sediments, practically complete in section from Lower Cambrian to Upper Devonian, nearly flat and of simple structure to the north, but becoming more complicated in the Hudson River slate region farther down the river. The district lying to the south is underlain by ancient and very complicated crystalline

gneisses, metamorphosed sediments in part, with great masses of igneous intrusions and bosses, and still farther south, in Westchester Co., are gently rolling parallel ridges, formed by a succession of limestone and schist belts. Near the city the underlying Fordham gneiss is frequently exposed. Several igneous masses are also penetrated, and a number of other formations have been barely avoided. The whole area is thickly drift covered, and this feature of course greatly obscures the geology. Recent greater elevation of the continent must also be taken into consideration, since it has resulted in the cutting of inner gorges in most of the valleys (some of which have since been obscured by glaciation), and in the circulation of ground water at depths greater than the present, producing frequent rotten zones and occasional caves below the present ground water level. A wide variety of problems are thus presented, covering the fields of physiographic, glacial, petrographic, and structural geology.

To supplement unusually close field study, the author commanded the resources of an extensive drilling equipment. Wash rigs were used where possible, but the chop and oil-well rigs were usually necessary, and the shot and diamond drills were frequently resorted to. The cores of the latter were preserved, and in many cases subjected to microscopic study; and careful records were always kept of the percentage and condition of the core saved, the rate of progress of the drill, its behavior, the loss of water in the hole, etc. Special pumping tests were made in some of the holes to determine the porosity and perviousness of the rock, this being of course a vital feature in the construction of pressure tunnels.

After a résumé of the geology and physiography of the district, and the principles involved in their interpretation, the author proceeds to a discussion of a number of type problems. Passing briefly over the considerations—chiefly physiographic—which led to the selection of the present aqueduct line, he takes up rather fully the problem of selecting a suitable crossing under the Hudson River. Detailed exploration of a number of points was made, and the Storm King locality finally selected as the most advantageous, chiefly because of the character of the rock, which is a slightly gneissoid granite, in striking contrast to the slate and limestone belts over which the river flows at the other points explored. Drilling at this locality showed bedrock at the extraordinary depth of 751 feet, the assumption being that the gorge was here glacially oversteepened several hundred feet. The geological features involved in selecting the great Ashokan dam site are then considered; they deal chiefly with the character of the bedrock, the assortment and imperviousness of the overlying till, and the general glacial history of this locality.

The crossing of the Rondout Valley has proved one of the most serious difficulties encountered in the whole work, and very detailed study has been given it. This valley is four miles wide and heavily drift covered, and the author was given the problem of deciding on the possibility of driving a pressure tunnel, together with the best place and most favorable depth for such a work. This required the determination of the topography of the buried valley floor; the position, within five feet at any given point, of any one of the twelve irregularly dipping and faulted formations in this valley; the structural and petrologic condition of each, with regard to porosity; and a study of the underground water circulation. While frequent recourse was had, of necessity, to diamond drilling, it was of course very important to determine which sections might safely be left without testing in this expensive and tedious manner. It was decided that the limestones must be avoided, because of their liability to solution by water under such great head, and likewise a heavy but brittle grit, because of the free circulation through it. Under this general type fall most of the other problems, which are concerned largely with the crossing of these old buried valleys. In New York City itself, however, some interesting complications are introduced by the value of the ground, the heavy traffic, etc.

It is impossible in this review to do more than give a general idea of the type of problems encountered; the practical value of the book lies in its complete presentation of the data at hand, and its faithful delineation of the lines of reasoning followed. The numerous and excellent plates and figures greatly clarify the text and enhance its interest. There seems little doubt that such geological work will come more and more into demand as its real value becomes recognized by engineers, and it is fortunate that one of the pioneers has been able in this report to sum up his experience and evaluate the various methods of attack. The author is to be congratulated, not only upon the success which later explorations have conferred upon his geological predictions, but upon the wisdom which he has displayed in presenting his report in so efficient and timely a manner.

G. S. Rogers

Daly, Reginald A. "The Nature of Volcanic Action," *Proc. Amer. Acad. Arts and Sci.*, XLVII (1911), 3, pp. 47–122.

In this highly suggestive paper Professor Daly has summed up and correlated a large part of his researches and speculations upon igneous rocks into a systematic hypothesis of volcanic action. The paper is an attempt to present a working hypothesis of vulcanism which will "co-

ordinate the accepted principles of vulcanology with each other and with the truths of plutonic geology"; and the group of conceptions advanced may be summarized in the name "substratum injection hypothesis," since the central thesis is that all vulcanism is the consequence of abyssal injection. The results arrived at in many of the papers which Professor Daly has published during the past few years are incorporated in the present treatise, and his recent studies in Hawaii are especially dwelt upon.

The theory postulates in the first place the existence of an acid shell in the earth's crust, overlain by the sedimentary pellicle, and underlain at a depth of about 40 kilometers by a basaltic substratum. The latter conception, although perhaps the most fundamental assumption in the whole theory, is advanced largely without argument, it being merely noted that most lava is of basaltic or andesitic composition. Taking the existence of this eruptible substratum for granted, then, the author proceeds to formulate the preliminary to vulcanism generally accepted as essential, viz., abyssal fissuring and magmatic injection. As the magma rises nearer the surface the great change in conditions will lead to certain immediate and direct consequences. In the first place, the basaltic magma will undergo an expansion of 1.5–6 per cent, energy being thus formed which may be available for opening fissures; secondly, the superheat existing in the magma will probably cause the assimilation of the wall rock, a point more fully discussed in a well-known former paper of the author's; and finally, the gases dissolved in the magma will tend to rise, supersaturating its upper levels, and finally separating as bubbles and collecting under the roof of the batholithic chamber. Emphasis is laid upon the necessity of defining the nature of these gases, since important functions are later to be ascribed to them. They are classified as magmatic and phreatic, the former class being made up of juvenile and resurgent (those derived from the country rock), and the latter of vadose and connate (those trapped in sediments).

The three phases of volcanic action are then fully considered. In fissure eruptions, which are always basaltic, the magma is highly superheated, as indicated by the low angle of slope and the great length of the flow. That no assimilation of acid country rock has taken place must be due to the fact that the feeding channel is always narrow. Expansion of the magma and the separation of its gases as indicated above are doubtless features in the effusion of such floods, although orogenic action is probably necessary to cause the initial abyssal fissuring. The second phase described is one less generally considered—eruption through local foundering. This is conceived as taking place when the magma is of

great size and is superheated sufficiently to allow of extensive assimilation of the overlying acid rock. It works its way up partly by piecemeal stoping of the roof, but a point is finally reached when a great part of the latter will cave in and founder in the fluid magma below. The assimilation of the surrounding rocks alters the composition of the latter, giving rise to a differentiation which results in the collecting of the acid phases at the top. The upper portions of the magma, which are usually liparitic, may overflow and produce a formation somewhat similar to a fissure eruption, but differing from it in being acid and in occurring in one thick flow rather than in several superposed sheets. The 600-meter sheet of rhyolite in Yellowstone Park is explained in this way. The fact that the geysers require more heat than such a flow can well supply is also accepted as a confirmatory indication that the rhyolite is not a true flow, but is merely the top layer of a great batholith which is basic in its lowest levels.

The paper, however, deals chiefly with the question of central eruptions, and the first problem presented is that of the opening and localization of the vent. If there be a pre-existent fissure it is doubtless susceptible of enlargement by the superheated lava; this may be accomplished by the solution and mechanical removal of the wall rock by the lava, or by the melting and explosive abrasion effects of the magmatic gas. If the latter become segregated and explosive, a diatreme, or tube surmounted by a funnel results, and this may also form in unfissured rock. In other cases the magmatic gases, highly heated and under great pressure, may collect in the hollows or cupolas of the roof of the batholithic chamber, thereby localizing and intensifying the stoping action of the magma. The latter may thus work the last few kilometers of its way to the surface unaided by a fissure.

A large part of the remainder of the paper is based upon an analysis of conditions in Kilauea. Mathematical calculations prove that an enormous amount of heat is lost at an open vent, and that the heat lost by radiation is over fifty times as much as that lost by conduction. Ordinary convection between the main feeding chamber and the vent is then proved inadequate to sustain heat in the latter. The conception of two-phase convection is then advanced: the magma rises continually because of its vesiculation, and, having discharged its gas at the surface of the lava lake, sinks again down the pipe to the main feeding chamber. This is the explanation of the currents in the Kilauea Lake and of the Old Faithful fountains which are thought to be located directly over the pipe, and to be due to the ever more rapid rise of the vesiculate magma as it nears the surface. Figures for the loss of density of the lava, after

a given amount of vesiculation, are adduced, and also for the velocity of solitary bubbles rising through a magma of given viscosity and at a given pressure; while the rate of rise of a mass of vesiculated lava in a non-vesiculate magma is estimated by the analogy of solid spheres moving under gravity in viscous liquids. These computations indicate that such a process is eminently possible, and it is regarded by the author as essential to the prolonged maintenance of activity. The action of the gases is further extended in the conception of the volcanic furnace. If the juvenile gases accumulate at the top of the magmatic chamber as indicated they will become concentrated in the actual volcanic pipe, and, according to the law of mass action, exothermic reactions on a large scale between the gases themselves are to be expected. Moreover, there may be other, and endothermic, compounds formed in the primitive earth, and the energy thus potentialized in the substratum will be liberated at these levels of greatly lessened pressure. Even before the magma reaches the surface such conditions will exist in the cupolas of the roof, and these highly heated gases, still under great pressure, will exercise a tremendous blowpiping action. The rôle of the gases in volcanic action is therefore a very important one.

The gas-fluxing hypothesis also explains the small size of observed volcanic pipes, since the slow passage of relatively small amounts of gas would not be expected to open a large vent. A very minute deformation would have a great effect on the rise of the gas, which would set all of the aforementioned processes in operation and reopen a dormant vent, so that the difficulty of explaining periodic vulcanism is lessened. Magmatic differentiation in central vents is to be largely explained upon principles which have been demonstrated in plutonic geology. Lava is however especially prone to differentiation, owing to the fact that it is kept fluid, but at a fairly low temperature, for a long time; that it has excellent opportunities for assimilating the wall rock; and that in each period of dormancy much of it passes through the stage of crystallization. Progress in magmatic differentiation decidedly favors explosiveness, which is due to the tension of the gases, so that it is only in fairly mature vents that this feature of volcanic activity is pronounced.

Direct offshoots of main abyssal injections have so far been considered. They form batholiths; and plutonic stocks and bosses are interpreted as cupolas in batholithic roofs. Sheets, dikes, and laccoliths are, however, distinctly satellitic, and soon lose thermal and hydrostatic communication with the main abyssal injection. It is only in the case of laccoliths that a mass of molten rock may be injected which will retain its heat for considerable periods; and such a mass may give rise

to subordinate vulcanism. Professor Daly considers Kilauea to be located upon a satellitic injection or laccolith. He formulates the characteristics of subordinate volcanoes as follows: brief activity, geologically speaking, small output of lava, a cluster grouping of the vents rather than an alignment, and the existence of traces of surface deformation due to the injection of the laccolith between the strata. Tertiary and Paleozoic examples are probably represented in Suabia and Scotland.

This theory of Professor Daly's is thus systematic and plausible, granting the existence of the basaltic substratum; and his practice of invoking the aid of physical formulas to support his ideas is highly commendable. To one who has not been closely following the work of Professor Daly along these lines, many of the somewhat novel views to which he casually refers in the present paper may be startling, but the more obvious objections to these at least have been disposed of in the author's previous articles. In a recent paper he estimates the amount of assimilation which a given mass of basalt can accomplish, and finds that about five mass-units of this rock will furnish the heat energy necessary for the solution of one mass-unit of granitic gneiss. A 5:1 mixture of rocks containing say 48 and 73 per cent of silica respectively would contain only about 52 per cent of that constituent, however, and it is evident that very extensive gravitative adjustment would be required to produce from this magma such a mass as the rhyolite flow at Yellowstone Park. The conception of Kilauea as a subordinate volcano is an interesting one; Professor Daly might perhaps have strengthened his argument by a calculation of the annual loss of heat of a laccolith of this size, and so have arrived at an estimate of the length of time that it could remain molten after injection. The fact that the whole theory is founded largely on the study of but one group of volcanoes might also be urged against it, but the paper nevertheless stands as a very interesting and suggestive discussion of those processes whose manifestations have long been the subject of speculation to the human race.

G. S. Rogers

Milch, L. "Ueber Plastizität der Mineralien und Gesteine," *Geolog. Rundschau*, Bd. II, Heft 3 (1911), 145–62.

Milch's paper presents the results of various investigators on the plasticity of minerals and rocks with a bibliography of the literature.

Perfect rigidity and plasticity are limiting conditions which no substances possess. A substance is perfectly rigid when it cannot be deformed by any amount of stress. It is perfectly plastic when it offers

no resistance to stress. Ordinarily, a substance is said to be plastic when it can be continuously deformed without rupture. Experiment shows that all substances are probably latently plastic depending on pressure, temperature, and time. Gypsum, stibnite, halite, calcite, ice, galena, cyanite, fluorite, apatite, anhydrite, bismuthunite, vivianite, lorandite, graphite, molybdenite, brucite, mica, and sylvite are found to be plastic at room temperature when subjected to pressure in one direction, as shown by the work of Brewster, Reusch, Bauer, Averbach, and Mügge. They are found to be more plastic in certain directions than in others. Mügge's experiments seem to indicate that plasticity in crystals is conditioned by "planes of translation," along which movement takes place when the crystal is deformed, and that crystals having "translation planes" are plastic under all physical conditions when adequate differential force is applied. About 77 crystal species have been tabulated by Vernadsky which show gliding planes, among them hornblende, topaz, dolomite, corundum, beryl, tourmaline, and epidote.

The conclusion seems justified that all substances, even those which have not been shown to be plastic by experiment, are plastic under the conditions which prevail in the deep parts of the earth, since the degree of plasticity increases with temperature and pressure. H. Tressa in 1864 showed that the plasticity of lead, aluminum, and ice was greatly increased under pressure. By means of pressure, W. Spring (1880) welded various metal powders and caused them to flow through an aperture. In 1902 and 1903 G. Tamman proved that flowage in these cases was due to internal friction and not to temporary melting.

After A. Heim had appealed to plasticity as the means by which mountain deformation is accomplished, confirmatory experiments seemed desirable. Pfaff's and Gümbel's experiments (1879 and 1880) were futile because they did not prevent fracture by supplying adequate pressure on all sides. In 1886 O. Mügge succeeded in getting plastic deformation of diopside, galena, and anhydrite by first imbedding them in lead or zinc and then subjecting them to pressures on all sides. In 1892, G. Kick imbedded test materials in molten alum, sulphur, and shellac inside a copper tube, and compressed them between the plates of a hydraulic press. He succeeded in getting plastic deformation of halite and marble. F. Rinne (1903), amplifying Kick's experiments, flattened calcite rhombohedra under a pressure of 1,200 Kg/qcm, but they partly broke into powder. Halite and sylvite, however, were deformed without fracture, loss of strength, or clearness. F. D. Adams (1910) continued Kick's experiments, and found that minerals were plastic in an inverse ratio to their hardness. Minerals less than 5 in

hardness were plastic. Fluorite was plastic. Diopside, hardness 5.5, developed polysynthetic twins. Apatite showed signs of plasticity. Orthoclase ruptured, but the particles were optically deformed. Quartz lacked plasticity, while marble was perfectly plastic. Granite suffered cataclastic deformation but became gneissose. In Kick's experiments the lateral resistance was insufficient and it was impossible to state how much pressure acted on the sample, since it was distributed over the metal tube, imbedding substance, and the sample itself. In order to overcome this trouble, F. D. Adams and C. G. Coker (1910) devised a thick tube of nickel steel, made of a steel block. The receiving tube was carefully bored out and polished and was slightly less in diameter than the cylinder of rock which was to be tested. The rock cylinder was inserted when the tube was hot. The compressing rod which fitted into the receiving tube was made of hard chrome-tungsten steel. The cartridge was weaker near the middle so as to prevent the material from flowing around the compressing rod. They succeeded in getting perfectly plastic deformation of Carrara marble and the strength tests showed an increase in strength with an increase in the deforming stress. The pressure exerted was equal to a depth of 41 miles of the earth's crust.

The following experiments illustrate the relation of temperature and pressure to plasticity. G. Tamman showed that for a series of metals an increase in temperature of 10 degrees caused a doubling of the rate of discharge through an aperture, all other conditions being equal. L. Milch showed that halite, melting point above 800°, is plastic at 200°C. Doelter observed that silicates pass through a transition stage of peculiar viscosity when passing from the crystalline to the molten state. Similarly, A. L. Day and E. T. Allen found that albite could be readily bent when in this state. "Protoklase" (see Rosenbusch, *Elemente der Gesteinslehre*, 65, 3d ed.) is explained by W. Salomon (1910) as the effect of the pressure of intrusion on magmas in this state. In 1901 Nicholson and Adams did not succeed in getting perfect plastic deformation of marble except at temperatures of 300°–400° C. In 1910, Adams and Coker succeeded in getting plastic deformation of marble at a lower pressure when it was heated than at ordinary temperatures.

The value of the time factor in plastic deformation is shown in the following experiments, which prove that extended plastication favors deformation. In 1910, F. D. Adams investigated the time factor by deforming a marble column one minute and finding on immediate testing that it retained 60 per cent of its crushing strength. It retained 65.7 per cent of its crushing strength when tested 100 days later and retained

on an average about 84.7 per cent when subjected for 30 days to a gradually increasing pressure. When left two years in the apparatus, one cylinder had even gained in strength. A marble cylinder deformed slowly for 64 days had about double the crushing strength of one equally deformed in 10 minutes.

However, deformation of rocks without fracture in nature is not believed by all to mean plastic deformation. Grubenmann, Becke, and Van Hise have emphasized the importance of mineral elongation normal to the pressure by means of solution on maximum pressure surfaces and redeposition on surfaces of minimum pressure through the agency of water. Opinions are also divided on the relation between rock deformation and the deformation of their constituent minerals. A. Heim (1908) believes that rock deformation and mineral deformation are distinct. A rock may be deformed without fracture as a whole, whereas its individual minerals may in part be fractured and others deformed as plastic objects. T. Lehmann (1889) regards deformation which is accomplished without rock fracture as a whole but by the fracture of individual minerals as "bruchlos," deformation without fracture. Weinschenk disbelieves in plastic deformation in general, but admits its possibility in slates and marbles, and claims they always present evidence of fracture. He asserts that in many cases schistosity was developed by magmas crystallizing under differential pressure. Steinmann (1907) is opposed to the latent plasticity view of A. Heim, but admits that thickening and thinning of rock strata has been important. C. Schmidt (1908) is not opposed to the view that plasticity is possible at sufficient depth but believes that Heim has not allowed for sufficient depth in his assumptions. C. R. Van Hise, Becke, U. Grubenmann, have emphasized the action of water as an agent in causing deformation without fracture, but do not deny that plastic deformation may be possible.

E. Steitmann

Pirsson, L. V., and Rice, W. N. "Geology of Tripyramid Mountain," *Am. Jour. Sci.*, 4th ser., XXXI (April, 1911), 269–91. Figs. 6.

Pirsson, L. V. "Petrography of Tripyramid Mountain," *Am. Jour. Sci.*, 4th ser., XXXI (May, 1911), 405–31. Fig. 1, and analyses.

The first paper describes the geology of Tripyramid Mountain, N.H., and discusses the probable origin of the mountain. In the second the several rock types entering into the composition of the Tripyramid

laccolithic intrusion are described in detail, both megascopically and microscopically. These include gabbro (hessose), norite (andose), monzonite (monsonase), and alkalic syenite (nordmarkose) in concentric zonal arrangement with which are associated as dike rocks quartz syenite-aplite (liparase) and lamprophyres (grano-andose and hornblende-grano-andose). The modes of the several rocks are determined and compared with the norm calculated from the chemical analyses.

The several types are considered to be differentiation products from an original monzonitic magma. Occurring as complementary final products of the differentiation are the two classes of dike rocks. In the case of the basic dikes it is shown that magmas of similar chemical composition may produce rocks of markedly different mineralogical composition—the essexite and camptonite dikes.

A brief general discussion follows on the broader application of the principles derived from the study of this peculiar aggregation of rocks, and the author concludes with a speculation concerning the origin of the alkalic magma.

A. W. Stickney

Sollas, W. J., and McKay, Alexander. *The Rocks of Cape Colville Peninsula, Auckland, New Zealand.* Two vols. Wellington, 1905 and 1906. Pp. 289 and 215. Illustrated.

These two volumes constitute a report relating to the Hauraki goldfields of the Auckland Provincial District, and mainly to Cape Colville Peninsula. The preliminary part of the report, of over a hundred pages, by Alexander McKay, government geologist of New Zealand, gives a general introduction to the geology of the district. The remainder of the first volume and the greater part of the second is taken up with petrographic descriptions of some four hundred thin sections of rocks from the Colville Peninsula; the determinations and petrographical descriptions by Professor Sollas, and the illustrations and notes as to locality, formation, etc., by Mr. McKay. There are also described ninety-two thin sections from other parts of New Zealand, including the Cheviot Hills and the east shore of Palliser Bay, Wellington.

The volumes are profusely illustrated with hundreds of full-page halftones of thin sections, a most excellent though expensive method of assisting a reader to obtain an idea of the individual rock specimens. Unfortunately many of the halftones are not so sharp as they might be, but the work, on the whole, is the most elaborate catalogue of rock slides yet attempted.

Albert Johannsen

THOMAS, HERBERT HENRY. "The Skomer Volcanic Series (Pembrokeshire)," *Quart. Jour. Geol. Soc.*, LXVII (1911), 175–212. Figs. 13; map 1, and analyses.

The extreme west coast of Pembrokeshire, England, with the immediately outlying islands to the west, of which Skomer Island is the largest, consist for the greater part of a succession of lava flows. The rocks furnish some unusual mineral associations; and two new rock types are developed and described. A descriptive bibliography relating to the geology of Skomer Island is given.

Stratigraphic evidence shows the volcanic rocks to be pre-Upper Llandovery, probably lower Arenig in age. The rocks are mainly a succession of thin subaerial lava flows of considerable lateral extent with which are associated a few doleritic sills representing a later intrusive stage. Interbedded with the volcanics are thin beds of conglomerates, quartzites, and red clays.

The petrography of eight distinct types of igneous rocks with several variants is described in detail, and their geographical distribution given. The rocks include soda-rhyolites and felsites, soda-trachytes, keratophyres, mugearites, olivine basalts, and olivine dolerites; and the two new types skomerite and marloesite.

These two new types are porphyritic rocks of rather basic composition, characterized by the association of a high proportion of albite with olivine and augite. The name skomerite is applied to a rock consisting of porphyritic laths of somewhat altered albite-oligoclase, subidiomorphic augite, and small idiomorphic crystals of olivine, in a groundmass of unoriented albite-oligoclase laths. Marloesite is described as containing glomeroporphyritic crystals of albite-oligoclase and altered olivine in a fine-grained groundmass of subidiomorphic augite, albite microlites, soda-bearing hornblende, and accessory iron minerals.

The more acid rocks of this series show interesting mineralogical variations from the generally recognized mineral associations. As the most notable peculiarity, these rocks contain soda-rich feldspar phenocrysts in intimate association with porphyritic crystals of olivine, hypersthene, and augite. The author recognizes the possibility of an original, more basic character of the rocks and a subsequent increase in soda-rich feldspar by albitization, but concludes, on good evidence, that the albite for the dominate part is original.

The rocks show an extrusive sequence from acid to basic and basic to acid, with a resulting frequent repetition of the same types of rocks.

A. W. STICKNEY


THE SOAP
THAT TAKES THE PALM
FOR TOILET AND BATH
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HAND SAPOLIO

VOLUME XX NUMBER 6

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A SEMI-QUARTERLY

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MICROSCOPICAL PETROGRAPHY FROM THE QUANTITATIVE VIEWPOINT

FRED. EUGENE WRIGHT
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INTRODUCTION

The development of petrology has been along the lines of normal growth followed by other sciences. From the Stone age on, people have had to do with rocks and have gathered, in the course of the centuries, a vast amount of information about them, their characteristics, their modes of occurrence, and their uses in practical life. Different rock types have received different names, and, up to the last century, were classified according to their general appearance and the purposes they served: Fine-grained rocks, like phonolites, the component minerals of which could not be distinguished by the unaided eye, were considered homogeneous and grouped with minerals, until chemists were able to show by partial analysis that part of the rock was soluble in acid and part insoluble. With the advent of the petrographic microscope, a new and fascinating world was opened to the student of rocks, and for some decades the interest was centered in the qualitative description of rocks, their mineral composition, and their textures. It was virgin land for the petrologist to explore, and the methods he adopted were the methods of reconnaissance, analogous to those employed by the geologist, who

visits a new country, like Alaska, to obtain a general idea of the geologic lay of the land and the rock types there represented. During this reconnaissance period, petrography, or rock description, was the prominent feature of petrology, as the thick papers of that time testify. Men were interested in rock types and rock classification. They wished to cover the entire field, and to do so had, of necessity, to adopt the methods of reconnaissance. Their methods and their classifications were all essentially qualitative in nature. After this preliminary work came the more detailed investigations, such as are represented in geology by folio and economic work with large-scale base-maps and only limited areas to cover in a given time.

A science must always develop from the qualitative to the quantitative, and the process is necessarily a gradual one. In science the term qualitative is usually applied to statements in which no definite limits to the quantities involved are expressed, while in quantitative statements such limits are definitely set. These limits may vary widely in their order of magnitude and one quantitative statement may be only roughly quantitative (first approximation) while a second may be highly precise. No observations are ever absolutely accurate; the absolute quantitative cannot be attained in the physical world and the idea of limits or degrees of approximation to truth (probable error) pervades all science. Such limits establish at once boundary lines or fences within which speculation must be held. In a qualitative statement such limits are not given, with the result that they may be arbitrarily extended or decreased by the investigator as the exigencies of his case demand. The smaller the limits in quantitative statement the higher the degree of approximation to truth, the fewer the possibilities for misinterpretation, and the greater the probabilities for correct generalization by the scientist. The growth of a science rests, in part at least, on the development of exact methods of attack and on the precise data of measurement accumulated thereby.

The observer who applies only reconnaissance methods to detailed work requiring exact methods is doing an injustice to the work, and is actually wasting his time, because such work has to

be done over later on. A mechanic who attempts to make a fine spirit level or microscope with poor tools cannot produce a good job. A petrologist on detailed work who describes rocks in the way they were described thirty years ago, and uses the microscope as it was then used, is doing an injustice, not only to the reader, but to the microscope and the tools of precision which are now placed at his disposal.

There is a genuine pleasure on the other hand, in making the most out of the tools we have, and in gathering data, the accuracy of which we know definitely and can state in terms which will be intelligible to observers a century hence. In short, it is only by the accumulation of tangible facts, and grouping of such facts by correct generalization, that real progress is made. From a few facts a mind of genius may intuitively infer and state a correct generalization which covers a whole group of facts to be discovered later, but most of us are not in that class, and it is our duty to assemble the facts—facts which are real facts, based on precise data of observation.

Strictly speaking, quantitative work means control over all parts of a given system. The order of accuracy of all measurements made is definitely known and any observer at a later date should be able to repeat the measurements and obtain similar results. The system is, in short, reproducible. Quantitative work is tangible throughout and we know definitely its behavior at all times during our observations. In qualitative work, on the other hand, the system is imperfectly defined, no definite limits are set, and the results, obtained, lack precision; their probable error is unknown and they are indefinite and uncertain to that extent. A strictly quantitative piece of work, the accuracy of which is adequately stated, produces on the observer, and on the reader as well, a feeling of confidence and stability, which qualitative work with its uncertain elements can never produce. A sense of control and mastery over the factors of an intricate system is a natural sequence of good quantitative work and is, psychologically, one of the greatest rewards granted to the student of nature.

There is still another feature which may be emphasized. In

attacking a problem, the different methods employed should be of about the same order of accuracy. It is useless to conclude that because precise methods are used on one part of a problem, the final result will be of the same order of accuracy, no matter what other methods are employed. The different methods should be co-ordinated and the observer should exercise proper judgment in applying his methods. Thus in rough traversing it would be a waste of time to use a theodolite and to read angles to seconds and then to measure the distances by pacing; or, vice versa, to attempt accurate triangulation with a pocket compass even though the base line be most carefully measured. There are cases, on the other hand, where certain mechanical operations, which are complete in themselves, can be readily and accurately performed, as, for example, the weighing of chemical precipitates; in this instance, it would be obviously improper to weigh the precipitate on a rough hand-balance, even though the probable error, resulting from such a procedure, might be within the probable error of the chemical methods employed. The order of accuracy of the final result would be unnecessarily decreased thereby, since its probable error is a direct function of the probable errors of the different steps involved in the process. To apply these principles successfully to actual problems requires critical judgment on the part of the observer.

All of this seems obvious, but it is not always realized in practice. Instruments are used, but their adjustment is rarely tested. Extinction angles are measured to the minute, and so stated, but the observer may fail to test the adjustment of his microscope and the nicols may be out half a degree or more.

The same holds true of the use of quantitative data. From a series of known facts a scientist evolves a theory and then searches for further data to substantiate or disprove his theory. This course of procedure is right, provided he examine critically into the data themselves—how they were obtained, their probable errors, and so forth.

The use of mathematics in this connection is important. Mathematics is a system of highly perfected logic, expressed in the form of symbols, and can be applied to practically all problems

in which the quantitative element enters. It is a highly developed system and impressive to most of us but "Huxley warned us that the perfection of our mathematical mill is no guaranty of the quality of the grist."[1] If we put into our mill loose data with large probable errors we cannot expect our final results to be more than first approximations. The more accurate the initial data the more accurate and satisfactory the final result. A statement cast in mathematical form does not prove that it is correct even though the mathematics be rigidly true. Mathematics, because it is logical and concise, is often used to express, in general form, relations the exact numerical values of which are not definitely known—such values being then represented by appropriate symbols. For purposes of generalization and the framing of a theory by the logical grouping of observed facts into a simple co-ordinated system, mathematics is invaluable because it serves to express in a single sentence the results and essentials of a whole course of reasoning. The more accurate the facts and results thus used, the greater the degree of probability for correct generalization and the easier the process of such generalization. The non-mathematical reader may examine the premises on which any mathematical argument is based and then use his common-sense in testing the conclusions.

Quantitative work requires more time than qualitative work but petrography has now reached a stage where quantitative work is required. To the observer accustomed only to rapid qualitative methods, quantitative methods necessarily seem slow and irksome and not yielding of immediate results, and he may even be tempted to question whether such methods are really worth the while and repay the energy and time which must be put into them. But in petrography the qualitative reconnaissance period has passed and it is no longer permissible in good work to ignore the quantitative element altogether. It is only by the accumulation of precise data that many of the large problems of petrology will be solved, and until then the solutions will remain matters of opinion supported more or less by a slender foundation of fact. Never before has the need for exact evidence, both from the field and

[1] Extract from address by R. S. Woodward, "On the Mathematical Theories of the Earth," *Proc. Amer. Ass. Adv. Sci.*, 1889, p. 62.

from the laboratory, been felt in petrology as it is today. The pioneers have done the reconnaissance work for us and we must proceed along quantitative lines of attack before we can hope to obtain even approximate solutions of the big problems ahead. Each one of us may contribute his share and add his little stone to the structure by adopting the quantitative viewpoint and realizing its importance in his attitude toward science in general and petrology in particular. In petrology *the quality of our quantitative work is far more important than the quantity of our qualitative work.*

Having now considered the standards postulated by modern petrology, our next step will be to show that the present-day tools and methods of microscopical petrography measure up to these requirements and are furthermore easy of application and simple in principle. We base our judgment of the value of a tool or method on its effectiveness, its simplicity, its adjustable sensibility, and its range of applicability. An instrument whose sensibility can be adjusted to meet the different conditions of observation which may arise is obviously superior to an instrument whose sensibility is rigidly fixed and adapted for only one particular set of conditions. The range of applicability as a feature in any instrument should not be carried too far because practical experience has shown clearly that the so-called universal instruments are, as a rule, unsatisfactory and often do not accomplish in a thoroughly competent manner any one of the several purposes for which they are intended. To fulfil a given set of conditions adequately, it is usually necessary that a special instrument be designed for the purpose. Thus, a small caliber rifle may be admirably suited for small game, but for larger game it is wholly inadequate, and may do more harm than service in an emergency; vice versa, a large caliber rifle is of little value for hunting small game.

The first tools which are devised for a given purpose are usually affected by "children's diseases," as Dr. A. L. Day has expressed it, and only by careful mechanical attention can such troubles be eliminated. The instruments and methods of microscopical petrography have in large measure passed through and beyond this stage and have been developed to such an extent that practically all the optical properties of mineral grains can now be

determined easily and without complicated apparatus on favorable plates or grains 0.02 mm. in diameter and over. It may be of interest to indicate briefly a few of the methods which experience has shown to be most satisfactory in actual work.

ADJUSTMENT OF THE PETROGRAPHIC MICROSCOPE

In these methods it is assumed that the microscope is properly adjusted, otherwise the results obtained may be seriously in error. The simplest method for testing the adjustment of the petrographic microscope is probably the following: (1) Remove from the microscope all lenses—ocular, objective, and condenser—and point it directly at the sun whose rays are parallel and so intense that a rotation of less than 1′ of one of the nicols from the position of total extinction is readily discernible. When the nicols are accurately crossed the sun appears as a dim disk in the dark background. (2) Test the adjustment of the cross-hairs of the ocular to the principal planes of the crossed nicols by observing under the microscope (fitted with ocular and centered objective but not with condenser, and pointed directly at the sun) a cleavage plate of some mineral, as anhydrite, celestite, or anthophyllite, which shows parallel extinction. The cross-hairs of the ocular should then be parallel with the cleavage edge of the plate in its position of total extinction. (3) Insert the condenser and note that it is properly centered when the image of the substage diaphragm occupies the center of the eye-circle of the ocular. In this plan of adjustment the assumption is properly made that the draw-tube and the substage are in alignment and that the optical elements are correctly mounted—mechanical details which are satisfactorily met by modern instrument-makers.

THE OPTICAL PROPERTIES OF MINERALS

Passing now to the optical and crystallographical features on which mineral diagnosis under the microscope is based, we shall consider first their nomenclature. Both theory and experience have shown that for monochromatic light the variation in the optical properties of a given mineral with the direction can be adequately expressed and defined in the most general case by

reference to a triaxial ellipsoid, the principal axes of which are equal to the three principal refractive indices. Having given the lengths and positions of the three principal axes of this *optic ellipsoid* within the crystal, it is possible to predict definitely the optical behavior of any section cut from the crystal. The validity of the optic ellipsoid has been proved so frequently and its usefulness in practical work is so great that its importance, independent of all theory, in optical work cannot be too strongly emphasized. That this has not been adequately done in the past, is evident from the current terms used to designate the optical properties of a mineral and of a mineral section. Thus we determine whether a mineral is isotropic, uniaxial, or biaxial and classify it accordingly, but there is no collective term which states that by this determination we actually ascertain the particular type of optic ellipsoid by which the optical behavior can be expressed; whether by a triaxial ellipsoid in which the three principal axes are unequal, or by an ellipsoid of revolution in which one axis is unique and different in length from the other two equal axes, or by a sphere in which all three axes are of the same length. For this characteristic the term *optic ellipsoidity*[1] is here suggested as a suitable group expression; thus the *optic ellipsoidity* of a *biaxial* mineral may be considered *biaxial* (two axial ratios being required to define the shape of its ellipsoid); the *optic ellipsoidity* of a *uniaxial* mineral, *uniaxial* (one axial ratio being sufficient to define the shape of its optic ellipsoid); and the *optic ellipsoidity* of an *isotropic* mineral, *isoaxial* (the three axes of its optic ellipsoid being equal). The *optic ellipsoidity* of a mineral is one of its most important diagnostic features; it is employed as a primary group-characteristic in nearly all the determinative tables for use with the petrographic microscope which have been published.

The lengths of the principal axes of the optic ellipsoid are ascertained by measuring the *principal refractive indices* of the crystal. From these in turn the *principal birefringences*, the *optic axial angle*, and the *optical character of the mineral* can be derived; these last properties are, therefore, subordinate, in a

[1] The writer is indebted to Mr. C. E. van Orstrand of the U.S. Geological Survey for aid in devising both this term and the expression *optic ellipsity* noted below.

measure, to the refractive indices. But in ordinary mounted, thin sections no satisfactory method has yet been devised for measuring the refractive indices directly and the microscopist is forced, in consequence, to make use of the other properties which can be ascertained under these conditions but which do not express, even in aggregate, all the information embodied in the simple statement of the refractive indices. It is for this reason especially that so much emphasis is placed on methods for refractive index determination and in particular on the immersion method by means of which the refractive indices of minute, isolated mineral grains 0.01 mm. and over in diameter can be readily measured with a fair degree of accuracy.

For the complete description of the optical behavior of a mineral, it is essential to determine not only the lengths of the principal axes of the optic ellipsoid but also its position within the crystal. This is usually accomplished by means of *extinction angles* on crystal faces of known orientation. From the position of the optic ellipsoid within the crystal we are able to infer the system in which the mineral crystallizes, since this position depends, as Brewster was the first to show, on the symmetry of the crystal itself. By determining the *principal refractive indices* of a mineral and its *extinction angles* on plates of known orientation, we can thus define its *optic ellipsoid* and its *crystal system* and from these in turn derive the optical behavior of any section cut from the crystal.

Having given the optic ellipsoid of a mineral for a particular color of light, the directions of vibration (positions of extinction between crossed nicols) and the relative velocities of light waves entering normally to any given section of the mineral can be ascertained by considering the section to pass through the center of the optic ellipsoid and to cut out of the same an ellipse, along the major and minor axes of which the light vibrations take place and produce plane-polarized light waves, whose velocities of transmission are inversely proportional to the lengths of these axes. This ellipse may be called the *optic ellipse* of the section. The optic ellipse is completely defined when the length of its major and minor axes (refractive indices γ' and α') and their positions with

respect to some definite crystal direction in the plate (extinction angle) are given. In actual determinative work with thin sections, the lack of a satisfactory method for measuring refractive indices directly under the microscope is a serious difficulty and the observer is compelled to make use of other properties, as *birefringence* and the *relative axial lengths* or *axiality* of the *optic ellipse,* which can be determined under these conditions but which, as noted above, are less important than the refractive indices and do not express, even together, as much as the refractive indices do alone.

For the expression *axiality of the optic ellipse* the collective term *optic ellipsity* may be used to express the relative lengths of the axes of the optic ellipse of the section. This term is preferable to the usual term *optical character of the section or optical character of its elongation.* The term *optical character* serves primarily as a group expression for the terms *optically positive* and *optically negative.* Its further use, in the above sense as a term implying the determination, in plane-polarized light, of the relative lengths of the axes of the optic ellipse of any given section is not justifiable, because, in that case, the same term serves two masters and conveys to the mind two totally different impressions; and such usage is not conducive to precise statement. The term *optic ellipsity* or *axiality of the optic ellipse* may well be substituted for *optical character* in its second usage.

In practical mineral determination under the microscope the observer may ascertain, in monochromatic light: (*a*) the *optic ellipsoidity* of a mineral, whether *biaxial, uniaxial,* or *isoaxial;* (*b*) the absolute lengths of the principal axes of its optic ellipsoid ($=\alpha$, β, γ, the *principal refractive indices*); (*c*) the difference in absolute lengths of any two of the principal axes of its optic ellipsoid (=*principal birefringences*); (*d*) the angle between the normals to the two circular sections of the optic ellipsoid (=*optic axial angle*); (*e*) the principal axis which bisects the acute angle between the normals to the two circular sections of the optic ellipsoid (the *acute bisectrix* γ or α and with it the *optical character of the mineral* whether *positive* or *negative*); (*f*) the relative position of the optic ellipsoid within the crystal (usually ascertained by

means of *extinction angles* on known crystal faces) and with it the *crystal system* of the mineral.

Similarly for any given crystal section we can determine, in parallel polarized light, (*a*) its *optic ellipsity* or the *axiality of its optic ellipse* (relative lengths of the two axes of its optic ellipse); (*b*) its *refractive indices* γ' and α' (lengths of the major and minor axes of its optic ellipse); (*c*) its *birefringence* (measured by the difference in lengths of the major and minor axes of its optic ellipse); (*d*) relative positions of the axes of its optic ellipse to any crystallographic direction observed on the section (*extinction angle*).

These properties vary to a certain extent with the color of light used and give rise to phenomena of color and color dispersion which are useful in mineral diagnosis. These are briefly: *color; pleochroism; absorption; dispersion of mineral; variation in the principal birefringences; dispersion of the bisectrices; dispersion of the optic axes.*

With this brief statement in mind of the optical features which are made use of in practical mineral determination, it will now be in order for us to show that the methods of microscopical petrography measure up to the requirements emphasized in the introduction and are furthermore simple and easy of application. For this purpose it will be convenient to group the optical and crystallographic properties into two classes: those of the first class (*optic ellipsoidity, optic ellipsity, optical character of mineral, color, pleochroism, absorption, dispersion of the optic axes, dispersion of the bisectrices, crystal habit*) being ascertained ordinarily by direct observation without measurement, while for the second class (*refractive indices, birefringence, extinction angles, optic axial angles, cleavage angles*) the numerical results of actual measurement are required. This distinction is drawn somewhat arbitrarily and is not meant to imply that the properties of the first group are strictly qualitative in their nature but that they are treated at the present time in ordinary petrographic microscopic work as qualities of an object rather than quantities which must be definitely measured. With greater refinement in the methods of determination, some of the properties of the first class will un-

doubtedly be included in the second essentially quantitative group. In the following paragraphs a concise description of the essentials of a few of the best available methods for the determination of these properties will be given.

DETERMINATION OF THE OPTICAL PROPERTIES OF THE FIRST CLASS

For this group few new methods of determination have been developed in recent years; *color, pleochroism, absorption, crystal habit, dispersion of the optic axes and of the bisectrices* being ascertained by practically the same methods which have been in use since the introduction of the petrographic microscope.

The optic ellipsoidity.—In the determination of this feature, two methods, in particular, have proved useful in recent years: (*a*) Uniaxial minerals are readily distinguished from biaxial minerals, by noting that the achromatic brushes (zero isogyres) in interference figures from uniaxial plates are parallel with the principal nicol planes and pass through the center of the field on rotating the stage, while in biaxial minerals the dark bars (zero isogyres) of the interference figure rotate on rotation of the stage and may include any angle with the principal plane of the polarizer. If the dark axial bar in an interference figure does not remain straight and in the same azimuth on rotating the stage, the optic ellipsoidity is biaxial; otherwise the birefracting mineral is in general uniaxial.[1] (*b*) To ascertain whether a very weakly birefracting plate is isotropic or birefracting and at the same time to determine the relative value of the axes of its optic ellipse (its optic ellipsity), the sensitive tint plate should be inserted, not in the diagonal position as is usually the case, but in such a position that the axes of its optic ellipse include only a small angle with one of the principal nicol planes; under these conditions the field illumination due to the sensitive tint plate itself is very slight while its path difference is still effective. The changes in the faint color hues from the mineral grain are clearly visible against the darker background and extremely minute traces of birefringence can thus

[1] See F. Becke, *Denkschr. Wiener Akad. Wissen. Math.-Natur. Kl.*, LXXV, 1904; *Tscherm. Min. Pet. Mitteil.*, XXIV, 30, 1905; XXVII, 177–78, 1908.

be detected.[1] If the sensitive-tint plate be inserted in the diagonal position, it illuminates the field so strongly that the faint color differences from the mineral grain are veiled and often completely lost to view, especially if the grain be minute. The same method is applied with equal success to the determination of the optical character of very weakly birefracting minerals in convergent-polarized light.

The optical character can be determined on all sections in which at least one optic axis appears in the field by noting that the convexity of the axial bar (zero isogyre) passing through the optic axis is always directed toward the acute bisectrix.[2] On sections, perpendicular to the optic normal the acute bisectrix can be located by noting that the faint achromatic hyperbolas of the interference figure pass out of the field in the direction of the acute bisectrix[3] on rotating the stage. In case the plate is so thick that the interference colors are bright, the position of the acute bisectrix can also be ascertained by noting that the interference color is relatively lower in the quadrants containing the acute bisectrix than in the adjacent quadrants.[4] In thin rock sections the mineral plates of weak to medium birefringence do not often exhibit interference colors much above pale yellow of the first order and for such plates the second method is inadequate and the first should be used. The relative value of the acute bisectrix whether

[1] See F. E. Wright, "The Methods of Petro. Microsc. Research," Carnegie Inst. Washington, *Pub. 158*, 73, 1911. In the writer's microscope the sensitive tint plate is mounted in a rotating collar beneath the substage condenser and can be turned quickly from one quadrant to another, thus greatly facilitating its use in rapid routine work.

[2] The following concise statement of the rule for finding the sign of reaction of a section has recently been given by F. Rinne (*T.M.P.M.*, XXX, 321–23, 1911): A central uniaxial interference figure divides the field into four quadrants. Let the NE and SW quadrants be considered positive as usual and the adjacent quadrants negative. In biaxial minerals the areas NE and SW of the achromatic brushes (zero isogyres) taken with respect to the acute bisectrix may in like manner be considered positive. If now the sensitive tint plate be inserted so that the major axis γ of its optic ellipse points NE, SW, then the mineral is *optically positive* when the *positive quadrants or areas* of the interference figure are colored *blue* and *negative* when the *negative areas* are colored *blue*.

[3] F. E. Wright, *Amer. Jour. Sci.* (4), XVII, 387, 1904.

[4] F. Becke, *T.M.P.M.*, XVI, 181, 1897.

α or γ (the *optic ellipsity* of the section) can then be ascertained by use of the sensitive tint plate or by the quartz wedge in parallel polarized light.

MEASUREMENT OF THE OPTICAL PROPERTIES OF THE SECOND CLASS

A number of new methods have been suggested in recent years for the measurement of the optical properties of this class, with the result that satisfactory methods are now available for use even on minute mineral grains; the accuracy of the results attainable by these methods under the different conditions is known and the application of these methods is now a matter of routine.

Refractive indices.—For the measurement of refractive indices of minerals in the mounted thin section no accurate method has yet been devised; but on unmounted mineral grains and plates, measuring 0.01 mm. and over in diameter, the refractive indices can be readily determined by the immersion method with an accuracy of ±0.001 for sodium light on isolated favorable sections. For this method a set of liquids of known refractivity is essential. The following set is used at present in the Geophysical Laboratory:

Refractive Indices	Mixtures of
1.450–1.475	Kerosene and turpentine
1.480–1.535	Turpentine and ethylene bromide or clove oil
1.540–1.635	Clove oil and α-monobromnaphthalene
1.640–1.655	α-monobromnaphthalene and α-monochlornaphthalene
1.660–1.740	α-monobromnaphthalene and methylene iodide
1.740–1.785	Sulfur dissolved in methylene iodide
1.790–2.050	Methylene iodide, arsenic sulfide, sulfur and tin iodide.[1]
2.055–2.750	Glass produced by melting amorphous sulfur and selenium in different proportions. The mineral grains to be tested are immersed in the molten liquid but are examined after it has cooled and hardened to a red-colored glass.[2]

[1] Dr. H. E. Merwin of this laboratory has recently made a detailed study of these highly refracting mixtures, their preparation, and their permanency. The results of his work are to appear shortly in the *Amer. Jour. Sci.*

See also O. Maschke, *Pogg. Ann.* CXLV, 565, 1872; *Wiedemann's Ann.*, XI, 722, 1880; J. Thoulet, *Bull. Soc. Min. France*, III, 62, 1880; H. Ambronn, *Ber. Sächs. Gesell. d. Wissen. Math. Phys. Kl.*, 1–8, 1896; J. L. C. Schroeder van der Kolk, *Zeitschr. f. Wissen. Mikrosk.* VIII., 458, 1898; F. E. Wright, *T.M.P.M.*, XX, 239, 1901; *Amer. Jour. Sci.* (4), XVII, 385, 1904; Carnegie Inst. Wash. *Pub. 158*, p. 98, 1911.

[2] The refractive indices of these glasses were measured in lithium-light and not in sodium-light, as is the case with all the liquid mixtures in this list.

In this series the refractive index of each liquid for sodium light is 0.005 higher than that of the liquid immediately preceding it. In choosing these liquids the guiding factors were stability, miscibility, and low dispersion. The refractive indices were measured on a total refractometer up to 1.74; above this by the hollow-prism method in sodium light. In place of the hollow prism Dr. Merwin has recently found a prism satisfactory which is made by fusing two narrow strips of plane glass (selected microscope object glass) together at one end so that their plane surfaces below the joint include an angle of 35° to 45°. A drop of the highly refractive liquid is then placed in the wedge-shaped space between the glass plates and adheres by capillarity to their plane surfaces, thus assuming the required prism shape. The liquids are kept conveniently in small dropping bottles with ground-glass stopper and cap, which interposes two ground joints to prevent evaporation. Experience has shown that the liquids so kept do not vary over 0.002 in a year, while the average change in the refractive index of a liquid is about 0.001 decrease for every 3° C. rise in temperature. By using obliquely incident light or by observing the Becke line, it is possible to ascertain at a glance whether the refractive index of a particular grain is above, below, or about equal to, that of the liquid.

In case the mineral grain has a higher refractive index than the liquid, it acts as a lens on an incident pencil of rays and increases their convergency; if its refractivity is lower than that of the liquid, it diverges the incident rays. This difference in behavior is best shown by a pencil of oblique rays; these are concentrated on the distant side of a higher refracting mineral grain opposite to that at which the incident rays impinge; in a lower refracting grain they are concentrated on the near side. In both instances the two margins of the mineral grains appear unequally illuminated; if the light be incident from the left, the bright band of light appears on the right margin of the higher refracting grain, and on the left margin of the lower refracting grain. In case both mineral and liquid have the same refractivity for yellow or green light, the difference in dispersion between liquid and mineral gives rise to characteristic phenomena. The dispersion for liquids is in general

greater than that for solids and in the present instance the liquid will have a lower refractive index than the mineral for red and a higher refractive index for blue, with the result that the red rays are concentrated along the one margin of the grain and the blue rays on the opposite side. The grain appears fringed with colored margins, red or orange on the one side and pale blue on the opposite side. If the intensity of illumination on both sides of the grains is about equal, the refractive index of mineral and liquid are equal for the central part of the visible spectrum.

Obliquely incident light is most readily obtained by placing the forefinger between the substage reflector and the polarizer and casting a shadow over half the field. The error of such a determination in white light is less than ± 0.005 on good sections, while if monochromatic light be used and care taken to select clear single grains, the error may be reduced to ± 0.001. If the grain be anisotropic, the three principal refractive indices α, β, γ can be determined by placing the grain in such positions that the parallel polarized light waves from the lower nicol vibrate, in passing through the crystal, parallel to one of the three principal axes of the optic ellipsoid.

The chief difficulty in the measurement of the refractive indices of minute grains or plates in the thin section, is one of mechanical subdivision; the grains occur frequently in fine, overlapping aggregates, often imbedded in glass; and it is not an easy task under these conditions to find a clear, isolated grain on which measurements can be made.

The materials for the set of refractive liquids noted above can be readily obtained from dealers in chemical supplies and the entire series prepared for use in a few hours' time. With the set of refractive liquids at hand the refractive indices of a mineral grain can be readily ascertained within ± 0.005 and one of the most important optical constants of the mineral thus determined. It is a matter of surprise, in view of the ease and facility with which this method can be applied, that it is so little used by petrologists and by chemists.

Birefringence.—For the measurement of birefringence, extinction angles, and optic axial angles a specially constructed ocular

has been found convenient.[1] This ocular consists essentially of a metal holder, which fits into the microscope tube as an ordinary ocular and acts as a support for certain plates which are inserted in the lower focal plane of a Ramsden eyepiece above. Cross-hairs are attached to the base of the cylinder support for the Ramsden eyepiece and are viewed by it simultaneously with the upper surfaces of the inserted wedges or plates.

For the measurement of the birefringence a graduated combination quartz wedge is used which is so cut that the 0.1 mm. divisions of the scale on its upper surface give directly path differences in 10 $\mu\mu$ for sodium light. By its use together with a cap nicol, the path difference in sodium light or order of interference color in white light can be readily ascertained, the wedge being inserted in the diagonal position until the black band of exact compensation is reached; the division of the scale covered by the black band is then the path difference in 10 $\mu\mu$. In the case of thick plates the point of the line of compensation should be first determined approximately in white light; otherwise the correct line of compensation may not be selected when monochromatic light is used. The path difference is directly dependent on two factors: the thickness of the plate and its birefringence. The simplest method for obtaining the thickness of a mounted plate or grain is to focus with a high-power objective first on its upper surface and then on its lower surface, as seen through the plate or grain itself. The amount of movement of the fine adjustment screw during this operation is the apparent thickness of the plate or grain, provided, of course, the fine adjustment screw is accurately constructed. The true thickness is obtained by multiplying the apparent thickness by the average refractive index of the plate. Experience has shown that under these conditions an error of 5 or even 10 per cent[2] may be made, especially if the plate be very thin, on thicker plates and grains the percentage error, due to imperfect focusing, is correspondingly less. To insure greater accuracy, the average of a series of determinations on the same plate should therefore be taken.

[1] F. E. Wright, *Amer. Jour. Sci.* (4) XXIX, 415–26, 1910.

[2] See F. E. Wright, *Amer. Jour. Sci.* (4), XXIX, 416, 1910.

The quotient of the two values thus obtained—path difference divided by thickness of plate—is the birefringence. The probable error of the determination under these conditions with good sections may be 10 per cent; for ordinary minerals this means an error of one or more units in the third decimal place.

The extinction angle for a given crystal face is the angle between a definite crystallographic direction on the face and one of the axes of its optic ellipse. With sharply developed crystallites or with minerals exhibiting sharp cleavage lines the error resulting from incorrect setting of the crystallographic direction parallel with the vertical cross-hair in the ocular is practically negligible; with less sharply defined crystallographic directions, the settings are of course less accurate; but as this is due to the crystal development and not to the method, the observer can only accept the situation as he finds it; the only probable error over which he has direct control centers essentially in the determination of the position of extinction. Since the eye is sensitive only down to a certain limit (threshold value, on an average about 0.001 meter-candle), it is evident that for all positions of the crystal plate between crossed nicols for which the intensity of the emergent light is below this limit, the plate will appear dark. In ordinary microscope work the angular range of this area of darkness varies from 1° to 2°, depending on the conditions of illumination and the eye of the observer; the error of a single determination may amount to 1° under certain conditions. By repeating such determinations the probable error can be materially reduced. But more accurate results can be obtained by using special devices which have been constructed for the purpose. Of these the bi-quartz wedge plate[1] has the advantage of adjustable sensibility to meet the different conditions of observation which arise. It is a combination of a right-handed quartz plate with a left-handed quartz wedge, and of a left-handed quartz plate with a right-handed wedge, all cut normal to the axis and so mounted that the points of exact compensation in each half are in alignment. The position of extinction of a mineral is determined with this device by noting that, on its insertion, the parts of the mineral plate covered by the adjacent

[1] F. E. Wright, *Amer. Jour. Sci.* (4), XXVI, 377–78, 1908.

halves of the wedge show the same degree of illumination. If the mineral be not in the position of total extinction the halves are not equally illuminated. Experience has shown that with this device the probable error of a single setting on a favorable section is about $\pm 10'$. The bi-quartz wedge plate is mounted in a metal carriage which in turn fits into the ocular holder described above. This bi-quartz wedge plate may also serve on dark days for the adjustment of the nicols in the petrographic microscope.

Optical axial angles are most readily measured by means of the 0.1 mm. co-ordinate micrometer disk[1] which in its metal-mounting fits in the ocular holder noted above. On favorable sections (0.025 mm. and over in diameter) the probable error of measurements with this plate is about $\pm 1°$ in case both optic axes appear in the field of vision and $\pm 3°$ in case only one optic axis is visible. For measurements on mineral grains, the particles should be immersed in a liquid of the refractive index β to eliminate errors due to refraction on the uneven surfaces of the grains. In weakly birefracting substances and interrupted sections the axial bars are less sharply defined and the values obtained thereon are correspondingly less accurate.

The divisions of the co-ordinate micrometer disk serve to locate the position of any point in the field. The interference figure, observed, is practically an orthographic projection of the interference figure formed in the upper focal plane of the objective and the use of co-ordinates to locate points in the field is therefore permissible. The angular values represented by these co-ordinates are determined, once for all, by means of an Abbe apertometer, or a graduated sphere or a scale in the lower focal plane of the substage condenser.[2] In case both optic axes, A_1 and A_2, appear in the field the course of procedure is simple. The crystal plate is turned until the plane of the optic axes, A_1A_2, in the interference figure (observed, together with the co-ordinate micrometer scale after insertion of the Bertrand lens, in the lower focal plane of the

[1] F. E. Wright, Amer. Jour. Sci. (4), XXIV, 316–69; XXIX, 423, 1910; XXXI, 157–211, 1911.

[2] These are discussed at length in *Amer. Jour. Sci.* (4), XXIV, 317–69, 1907; also in Carnegie Inst. Washington, *Pub. 158*, 1911.

Ramsden ocular) is parallel with the horizontal cross-hair of the ocular and its distance in this position from the center of the field recorded. The crossed nicols are then turned through a suitable angle (30° or 45°). The axial bars rotate in the opposite direction but the optic axial points, A_1 and A_2, remain stationary and dark; they are situated at the intersection of the axial bars with the horizontal line which marked the plane of the optic axes. The angular distance between the two optic axial points A_1 A_2, thus determined, is directly the optic axial angle $2E$ in air.

In case only one optic axis A_1 appears in the field of vision the method is more complicated and less accurate but in view of its usefulness it may be briefly outlined. It is based primarily on the rule of Biot-Fresnel which states that for light waves propagated in any given direction in a crystal the two lines of vibration bisect the angles between the projections of the two optic axes on the plane normal to the given direction of propagation. In an interference figure the line of vibration for any point which appears dark between crossed nicols is evidently contained in the extinguishing plane of the analyzer—otherwise it would not be dark. The plane of vibration for all points on the achromatic brushes (zero-isogyres) of an interference figure is therefore known. By locating the optic axis A_1 and any point P on the achromatic brush it is accordingly possible by applying the Biot-Fresnel rule to determine graphically the position of the second optic axis.[1] After having made the measurements in the interference figure, the observed co-ordinate values are first reduced to equivalent angular values in air and these in turn to corresponding values within the crystal by means of its average refractive index. These angles are then plotted in suitable projection (angle or stereographic)—the plane of the optic axes as a great circle parallel with the horizontal diameter, the principal plane of the polarizer in its two azimuths as diameters of the projection, the optic axis A_1 and the point P on the achromatic brush at the intersection of the recorded small circle (almucantar) co-ordinates. In this pro-

[1] See F. Becke, *T.M.P.M.*, XXIV, 35–44, 1905; XXVIII, 290, 1909; also F. E. Wright, *Amer. Jour. Sci.* (4), XXIV, 316–69, 1907; (4), XXXI, 157–210, 1911; Carnegie Inst. Wash. *Pub. 158*, 147–200, 1911.

jection the Biot-Fresnel rule is applied by first projecting the optic axis A_1 on the polar circle of the point P; the intersection, C, of this polar circle with the diameter which defines the position of the principal plane of the polarizer at the time of the observation determines in projection the line of vibration of P. The angle between the point C and the projection point A'_1 of the optic axis A_1 is half the angle between the lines of projection of the two optic axes. The point A'_2, the projection of the second optic axis A_2, is accordingly found by laying off on the polar circle from the point C an angle equal to A'_1C. The intersection of the great circle through P and the point A'_2 with the plane of the optic axes is obviously the second optic axis A_2 and the angle between the two axial points, A_1 and A_2, is the optic axial angle $2V$. The best results are obtained by this method on sections in which the optic axis A_1 is located about midway between the center and margin of the field and the point P on the achromatic brush in a similar position. As noted above, a probable error of $\pm 3°$ is possible with this method even on the most favorable sections. The error is proportionately larger on poor sections.

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GLACIATION IN THE TELLURIDE QUADRANGLE, COLORADO

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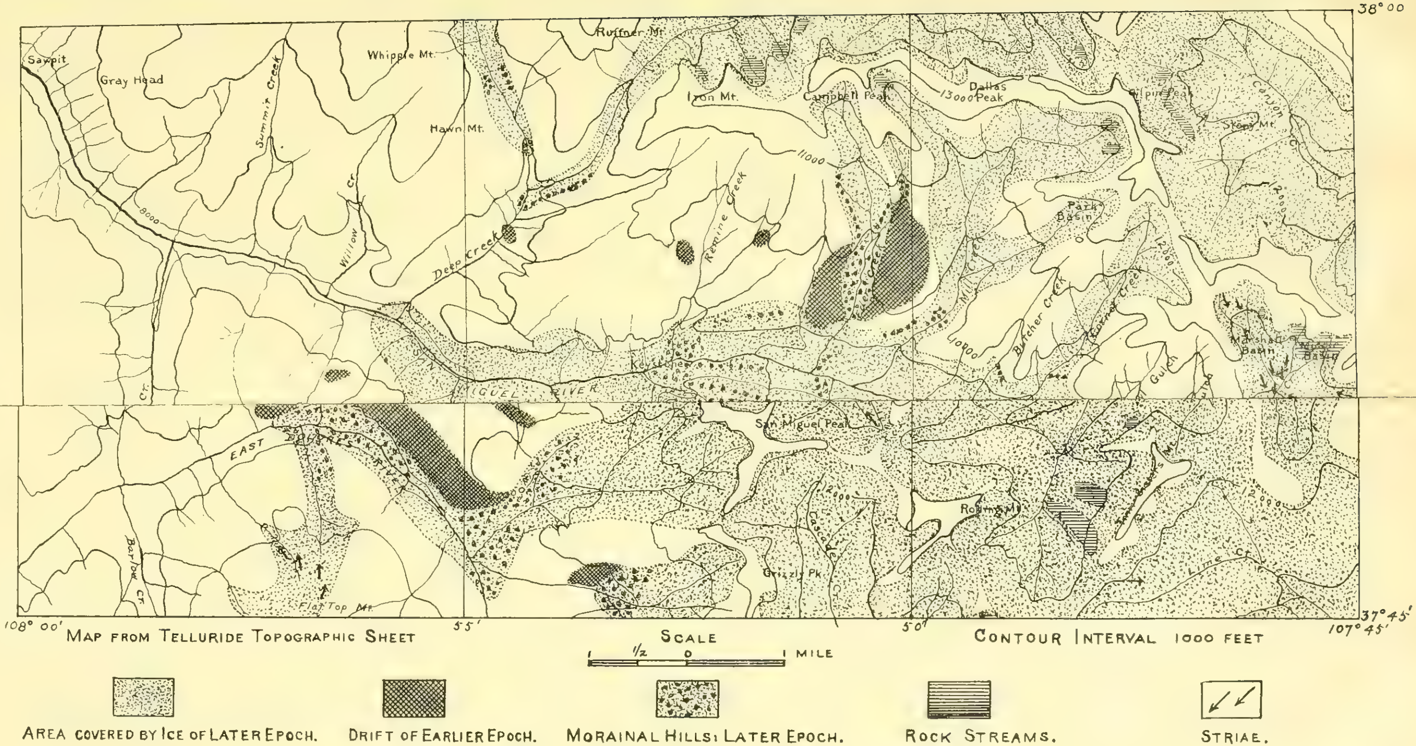
OUTLINE

[1] This paper presents primarily the results of work done by the author in the field seasons of 1904 and 1905, under the direction of Professor R. D. Salisbury. Acknowledgments are due, besides, to many observers who have done work in the same region, particularly to Mr. Whitman Cross, who has for some years been in charge of the general geological investigations in the San Juan Mountains, to Mr. L. L. Everly, who assumed equal responsibility with the author in the work of the first season, and to Mr. John T. Haworth, who rendered service as field assistant in the second season. —A. D. H.

PLATE I



MAP OF THE TELLURIDE QUADRANGLE, COLORADO

Showing the distribution of glacial formations. Glacial geology by Allen D. Hole, in 1904 and 1905, under the direction of Rollin D. Salisbury

MAP OF THE TELLURIDE QUADRANGLE, COLORADO

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PART I

LOCATION AND EXTENT OF AREA

The Telluride quadrangle, Colorado, lies in the southwestern part of the state about 60 miles from the western and 55 miles from the southern boundary. It is included between meridians 107° 45′ and 108° 0′ west longitude, and parallels 37° 45′ and 38° 0′ north latitude, having therefore a width of a little less than 14 miles, a length of a little more than 17 miles, and an area of over 235 square miles.

DRAINAGE

The greater part of the area of the quadrangle is drained by the San Miguel River, which flows northwest to join the Dolores, a tributary of Grand River; but the Uncompahgre River to the north, the Animas to the southeast, and headwaters of the Dolores to the southwest each receive some streams heading within this area; so that streams flow outward across the borders of the quadrangle toward practically all points of the compass, finally, however, to join their waters with those of the other tributaries of the Colorado River before reaching the sea.

TOPOGRAPHY

The chief topographic features of the quadrangle may be grouped under three heads, viz.:

1. The rugged peaks and ridges in the eastern half of the area, a part of the San Juan Mountains.

2. The isolated, loftier peaks of the Wilson group in the central part of the western half.

3. The plateau north and south of the Wilson group, cut by deep canyons in which flow the San Miguel, and the East Dolores rivers and their tributaries.

The highest point in the quadrangle is Mt. Wilson, near the western side, 14,250 feet above the sea; numerous peaks, however, in the eastern half rise above 13,500 feet, and ridges extend for miles with crests at an elevation greater than 13,000. The lowest point in the quadrangle is in the canyon of the San Miguel River, in the northwestern part, an elevation of 7,500 feet; but the plateau in which the canyon is cut has at most points an elevation of not less than 9,000 feet.

The topographic features as they exist today in the quadrangle are the result of agencies which have been in operation from a remote period in the history of the earth to the present time. The earlier include all those forces and processes which culminated in the relative elevation of the land thousands of feet above the sea, the ejection of enormous quantities of lava and other volcanic material, and the dissection of this elevated and ejected material by erosion, until, at the opening of Pleistocene time, the mountains, plateaus, and main stream channels must have had positions relatively much the same as they have now. The details of the topography, however, are due to agencies which have operated within Pleistocene and recent times; chief among these agencies which have produced results more or less well marked are: (1) agents of weathering, including freezing and other changes in temperature; (2) running water; (3) lakes and ponds; (4) moving masses of snow and ice, not glacial; (5) landslides; (6) glaciers.

GEOLOGICAL FORMATIONS

Observations in regard to the geology and topography of areas within this quadrangle have been made by a number of scientists, including members of the Hayden Survey and representatives of the War Department of the United States, as well as many others; the first detailed work to cover the entire area, however, was that undertaken by Mr. Whitman Cross and his associates, the results of which were published by the United States Geological Survey in the *Telluride Folio*, in 1899, from which the summary given below is largely taken.

Speaking generally, it may be said that so far as rocks near the surface are concerned, the plateau portion of the quadrangle is for the most part underlain by sedimentary formations, while the peaks and ridges in the mountainous portion are composed very largely of igneous rocks. Of the latter there are (1) various phases of intrusive bodies which in form include stocks, laccoliths, dikes, and sills, and in composition range from basalt to rhyolite, including andesite,

FIG. 1.—Dike in sandstone on the north side of the San Miguel River, one-fourth of a mile northeast of the mouth of Big Bear Creek. Looking northeast from a point 100 feet above the stream.

gabbro-diorite, diorite-monzonite, diorite-porphyry, monzonite, and granite-porphyry; and (2) widespread sheets of bedded extrusive rocks of three series named in order from the oldest, the San Juan, the Silverton, and the Potosi rhyolitic series.

The intrusive bodies vary in size from dikes whose maximum thickness is to be expressed in feet and inches, and which at best have contributed only in the most insignificant degree to the physiographic and structural features of the region (Fig. 1) to

stocks whose dimensions are to be expressed in miles, and which have given rise to many of the loftiest and most rugged peaks to be found within the area, as for example the Wilson group (Fig. 2) and Grizzly Peak.

With the exception of a few small outlying remnants, the bedded volcanic rocks are found only in the eastern half of the quadrangle where they form the lofty and rugged peaks and ridges of the San

FIG. 2.—The Wilson group of mountains, an eroded stock. Looking south of west from elevation about 11,200 feet at the mouth of Alta basin. The body of water shown in the foreground is a small temporary glacial lake formed by unequal distribution of drift.

Juan mountain front. The lowest member, the San Juan series, consists of andesitic tuffs, breccias, and agglomerates, cemented to some extent by minerals such as calcite deposited by circulating waters, so that in favorable positions steep, clifflike slopes are formed. Its maximum thickness is 2,000 feet. The intermediate series, named, after the publication of the *Telluride Folio*, the Silverton series, consists of alternating andesitic and rhyolitic flows with which are mingled sheets of tuff and breccia of andesite and

rhyolite, making up a maximum of 1,300 feet in thickness. This series results in topographic forms similar in some situations to those resulting from the erosion of the San Juan series, in others more closely resembling the steeper cliffs of the Potosi rhyolite. Of the upper, Potosi rhyolitic series, a maximum thickness of about 1,300 feet remains, consisting of a series of rhyolitic beds, the majority of which are flows, but some are tuffs. The area covered by this series in the quadrangle is comparatively very small, but topographically it is conspicuous, not only because it forms the summits of the highest peaks and ridges, but also because it weathers in remarkably steep cliff faces, showing often a vertical columnar structure, and where the direction or degree of the slope changes, bold, sharply angular outlines.

Below the bedded volcanic rocks in position there occur in order the following sedimentary strata, viz.: (1) the Telluride conglomerate, (2) Cretaceous shales and sandstones, (3) Jurassic shales, sandstones, and limestones, (4) Triassic sandstone and conglomerate, and (5) some sandstone and conglomerate probably of Permian age.[1]

These sedimentary rocks have influenced in various ways the course of events in the geological history of the quadrangle, and have been important factors in producing certain conspicuous topographic forms found there at present, as for example the steep walls of the canyon of the San Miguel River, due in many places to the presence of sandstones and conglomerates. For the most part these sedimentary strata retain their horizontal position except in certain cases in the immediate vicinity of bodies of intrusive volcanic rocks; one conspicuous monocline, however, is to be found west of the mountain front, and folds somewhat more complex in the southeastern corner of the quadrangle.

LITERATURE CONCERNING GLACIATION IN THIS AND ADJACENT QUADRANGLES

1877. The Hayden Geological Survey.—In Appendix A to the *Ninth Annual Report of the United States Geological and Geographical Survey of the Territories*, Dr. F. M. Endlich reports, under the heading "Ancient Glaciers in Southern

[1] Cross, *Engineer Mountain Folio*, p. 7, and various other publications there referred to.

Colorado," pp. 216–26, evidences of glaciation at a number of points in the San Juan Mountains. These evidences include *roches moutonnées*, grooved and striated rock in place, shallow lakes, and glacial drift in the form both of scattered erratic bowlders and moraines. As to the time relations involved, Dr. Endlich concludes (1) that at least one glacier, called by him the Conejos, was not older than late Tertiary time, and might be much more recent, basing his conclusion on the relation of its action to the basaltic lava flows; and (2) that the glacier which descended the Animas valley was of older date than those whose effects were to be seen near the headwaters of the different streams named. He does not, however, seem to mean that there were two separate stages of glaciation. The total work done by glaciers in modifying the preglacial topography he considers to have been slight; aside from this no estimate is made as to the amount of glacial erosion, amount of ice, or area covered when the ice was at its maximum.

1883. R. C. Hills.—In the *Proceedings of the Colorado Scientific Society*, Vol. I, in an article entitled "Extinct Glaciers of the San Juan Mountains," pp. 39–46, Mr. Hills cites evidences of glaciation from numerous points, and makes certain estimates as to the extent of the ice and the time relations involved. The following summary shows the more important points presented:

1. The ice attained a greater thickness and covered an area many times more extensive on western than on eastern slopes.

2. Glaciers were not confined to existing valleys, but at some remote period probably the entire western slope of the mountains, except perhaps the higher peaks, was covered with an unbroken sheet of ice. As evidence supporting this conclusion he mentions (*a*) the presence of large granite bowlders distributed 5 miles west of Durango; (*b*) erratics of eruptive rocks on mesas flanking the San Miguel River 35 miles from the source of the river; and (*c*) erratic bowlders within a short distance of Montrose.

3. The Animas Glacier was 1,200 to 1,500 feet thick "between Elbert and Silverton," and nearly 3 miles wide "a short distance above Elbert."

4. During the period of extension of the ice sheet the erosion of Upper and Middle Cretaceous rocks amounted to 200 to 500 feet.

5. Box canyons 50 to 100 feet deep have been eroded since the retreat of the local glaciers as in the Uncompahgre valley at Ouray and in the Animas valley above Elbert, etc.

6. The total extent of the old ice envelope is estimated at more than 4,500 square miles.

1893. George H. Stone.—In Vol. I of the *Journal of Geology*, pp. 471–75, Mr. Stone describes glacial phenomena found in the valley of the Las Animas River, and in some of the valleys tributary to it above Silverton. The moraines near Durango are noted, but the difference in age between the drift on the edge of the mesa lying east of the city and that lying near Animas City but little above the level of the river seems not to have been recognized. The total length of the Animas Glacier is given as about 70 miles, average slope of upper

surface 83 feet or more per mile, thickness near Silverton, 1,500 feet. Attention is also called to certain facts, viz.: (1) that striations on rock in place are relatively rare on account of the character of much of the outcropping volcanic rock; (2) that a comparatively small amount of morainal material is to be found; and (3) that the amount of outwash gravels in the form of terraces and valley train is large.

1899. George H. Stone.—In *Monograph 34, U.S. Geological Survey*, pp. 340–45, Mr. Stone repeats substantially what was published in the *Journal of Geology* in 1893 in regard to glacial phenomena in the valley of the Las Animas, and adds notes on evidences of glaciation in other valleys of the San Juan Mountains, viz., the San Miguel, Uncompahgre, and upper Rio Grande; and mentions as glaciated the upper parts of the valleys of Los Pinos, San Juan, Navajo, Chama, and other rivers of the western slopes of the mountains. Moraines, erratic bowlders, *roches moutonnées*, and outwash gravels are mentioned, and locations are given for some of the best-marked instances of such phenomena.

1899. Whitman Cross.—In the *Telluride Folio*, p. 15, Mr. Cross records evidences of glaciation as follows: (1) in the upper parts of some valleys, *roches moutonnées*, striated and polished rock in place, small lake basins, and glacial cirques; (2) at lower elevations in the principal valleys and on some ridges, glacial deposits consisting of angular and subangular bowlders, gravel, sand, and finer material, sometimes in the form of small moraines, sometimes in isolated patches scattered over the surface. The largest area of drift mapped lies east of the Lake Fork of the San Miguel River and is referred to the action of a stream of water which, at a time when the ice moving down Lake Fork was higher than the canyon walls, was believed to flow during the summer in a channel along the eastern side of the glacier to join the main fork of the San Miguel River near Keystone. Aside from a suggestion that ice from Lake Fork seemed to be present at a later date than in the main fork above Keystone, the time relations are not discussed.

1900. Arthur Coe Spencer.—In the *Twenty-first Annual Report of the United States Geological Survey*, pp. 156–59, Mr. Spencer names as evidences of glacial action in the Rico Mountains (1) certain topographic features, (2) a few instances of polished and striated bed rock, and (3) some deposits of glacial débris. He concludes that the amount of ice present was small, and that the time covered by glacial conditions in this group of mountains was short.

1905. Whitman Cross.—In the *Rico Folio*, pp. 6, 12, and 13, the evidences of glaciation named by Mr. Cross are much the same as those named by Mr. Spencer in the work last cited; there is added, however, a suggestion of two distinct glacial stages, viz.: (1) a recent stage referable to the close of the Wisconsin period, and (2) a pre-Wisconsin stage. The morainal deposits, *roches moutonnées* and striae, are referred to the former; high-level bowlder beds are classified as pre-Wisconsin in age though not necessarily glacial in origin.

1905. Whitman Cross.—In the *Needle Mountains Folio*, pp. 6, 11, and 12,

evidences of glacial action are noted at numerous places. The amount of morainal drift remaining in the quadrangle is observed to be relatively very small; the extent of grooved and polished surface of bare rocks, very large. From evidences of the latter kind within the quadrangle and from other evidences in adjacent quadrangles, the conclusion is reached that when glaciation was at its maximum the "greater part of the Needle Mountains area was buried beneath a thick mantle of ice and snow, from which only the higher summits projected." Only one stage of glaciation is recognized so far as observations made in this quadrangle are concerned.

1905. Whitman Cross and Ernest Howe.—In the *Silverton Folio* numerous references are made to the evidences of glacial action at points in various parts of the quadrangle. As in the *Needle Mountains Folio*, the small amount of morainal material is noted, as well as the extensive development of cirques. The authors express the opinion that the amount of glacial erosion in the glacial epoch recognized in the Silverton quadrangle was slight.

1906. T. C. Chamberlin and R. D. Salisbury.—In Vol. III of their *Geology*, pp. 334–36, Chamberlin and Salisbury include the San Juan Mountains in the term "mountains of southwestern Colorado," and, in addition to noting the former size and the altitude of the source of the glaciers in these mountains, state that the drift is referable to two or more glacial epochs.

1906. Whitman Cross and Ernest Howe.—In a paper entitled "Glacial Phenomena of the San Juan Mountains, Colorado," published in the *Bulletin of the Geological Society of America*, XVII, 251–74, Cross and Howe cite the evidences of glaciation at various points in the San Juan Mountains as noted above, and make mention of conclusive proof of two distinct stages of glaciation obtained especially in the Uncompahgre valley in the Ouray quadrangle in the summer of 1904. The chief differences noted with respect to the drift deposits of the two stages are (1) the slight modification due to weathering and erosion in the more recent deposits; relatively great changes in both these respects in the earlier; (2) the occurrence of the older drift at a greater distance from the mountains, capping ridges, and hills which had been formed by erosion before the last stage of glaciation; and (3) stratified deposits of gravel associated closely with the older deposits at relatively high elevations, and a series of gravel terraces intermediate in position between these and the earliest valley trains of the more recent stage.

1907. Whitman Cross and Ernest Howe.—In the *Ouray Folio*, pp. 7 and 15, the authors present again substantially the same data and conclusions in regard to glaciation in the Ouray quadrangle as were included in their paper just referred to on glaciation in the San Juan Mountains.

1909. Ernest Howe.—In *Professional Paper 67, U.S. Geological Survey*, Mr. Howe refers briefly in a number of places to the evidences of glaciation in the San Juan Mountains, but records no observations not included in publications already named above.

1910. Stephen R. Capps, Jr.—In the *Journal of Geology*, XVIII, 370 and

371, Mr. Capps refers to the striking similarity between the "rock streams" found at various points in the San Juan Mountains, and the "rock glaciers" of the Nizina region in Alaska. In regard to the latter he reaches the conclusion that they "are now in motion, moving in some such way as a glacier."

1910. Whitman Cross and Allen D. Hole.—In the *Engineer Mountain Folio*, pp. 8 and 9, evidences are given leading to the conclusion that the mountains of the quadrangle were subjected to glaciation at two distinct periods separated by a long interval of time.

GLACIAL PHENOMENA OF THE QUADRANGLE

As may be seen by reference to the literature cited above on glaciation in the region, complete detailed observations on the glacial phenomena of the Telluride quadrangle have not heretofore been made. By far the most complete account of such phenomena yet published is contained in the *Telluride Folio*, already referred to; but even there little reference is made to the details beyond what is necessary in illustrating general statements; and, moreover, especial attention is called to the fact that no attempt has been made to represent on the map all the deposits of glacial débris that were recognized. The overshadowing importance at that time of a careful study of the intricate relations involved in the volcanic rocks, and the demand for an early publication of the results of such study for the benefit of the extensive mining interests of the region no doubt fully justified the omission of many of the details relating to glacial action; the striking character, however, of some of the phenomena observed, and the aid which an understanding of the relations involved promised to give in the determination of some unsettled points in Quaternary history led to a systematic examination of the glacial phenomena of the entire quadrangle, the report on which here presented constitutes, therefore, a supplement to the conclusions previously published.

The evidences of glacial action found in the Telluride quadrangle include most of the characteristic marks of the work of glaciers as found in other localities, viz.: (1) cirques, (2) striated bed rock, (3) *roches moutonnées*, (4) lakes in rock basins, (5) moraines both in the form of ridges and of broad sheets with irregular, hummocky topography including undrained depressions, (6) unassorted drift including fragmental material of all sizes from fine silt to bowlders,

18 feet in diameter, and containing representatives of the various kinds of rock present in the basins from which the drift was derived, (7) striated bowlders included in the unassorted drift, (8) streams steep in gradient flowing in valleys U-shaped in cross-section, and (9) hanging valleys. Of the evidences named above it was found that a part of that referable to classes 5, 6, and 7 represents the work of an epoch or epochs of glaciation earlier than the most recent. Some of this earlier drift occurs in or near valleys in which ice of the latest epoch was present; but some in valleys which appear not to have been subject to the action of ice of so recent a time. Furthermore, the earlier drift is in some cases found on divides between valleys instead of on the slopes or bottom as is usually the case with the more recent drift, and in many cases glaciated valleys contain drift of the most recent epoch only. In view of these facts in regard to the distribution of drift of different epochs, the detailed descriptions of glacial phenomena in different basins and valleys have been grouped as follows:

I. Phenomena in each valley referred to glacial action of the more recent epoch.

II. Phenomena referred to glacial action distinctly earlier in time.

DESCRIPTION OF AREAS GLACIATED IN THE MORE RECENT EPOCH

VALLEY OF THE SAN MIGUEL RIVER

The San Miguel River is formed by the junction of Ingram and Bridal Veil creeks about two and one-half miles east of the city of Telluride. The walls of the valley near this point are, for much of their height, bare precipices, and rise from 2,000 to 3,000 feet above the bed of the stream. The channel of Ingram Creek is a continuation in direct line of the valley of the San Miguel River; but from a point a half a mile above its junction with Bridal Veil Creek to the level of the lower part of Ingram Basin, a vertical distance of over 1,000 feet, the gradient of the stream is practically that of the slope of the walls of the valley of the San Miguel on either side, so that the steep side walls of the valley of the San Miguel virtually meet each other to the east, forming a cul-de-sac which differs from

a typical cirque only in the fact that its walls are deeply notched by permanent streams (Fig. 3).

Below this cirquelike valley head the height of the walls and the steepness of their slopes gradually diminish until, just above Keystone six miles to the westward where deposits in the form of moraines are abundant, the height of the walls is not more than

FIG. 3.—Valley of the San Miguel River, elevation 9,000 feet; looking south of east from north side of valley. Note the flat bottom, the meandering stream, and the abrupt termination of the valley in the center of the view.

400 to 600 feet with a slope not steeper, in general, than 30 to 40 degrees. This comparatively low elevation of the top of the valley walls above the stream as shown just east of Keystone is due in part to the fact that the San Miguel River at this point has its channel in glacial drift, or in the silt of a lacustrine deposit which fills the channel cut in the underlying bed rock to a depth of probably 400 feet. From the morainal deposits in the vicinity of Keystone to the terminus of the glaciated area near the mouth of

Deep Creek, the valley of the San Miguel is a canyon with precipitous walls 1,000 feet high. Beyond the mouth of Deep Creek the canyon gradually increases in depth until, at Sawpit, at the northwest corner of the quadrangle, the stream is 1,700 feet below the level of the edge of the plateau in which it has cut its channel.

Drift in the valley of the San Miguel.—Drift in the form of valley train is found up to 100 feet above the stream at various points as at Newmire and Sawpit, and beyond the boundaries of the quadrangle; but the lowest point reached by the ice in the more recent stage of glaciation is near the mouth of Deep Creek. At this point the north wall of the valley is precipitous, its south wall worn and weathered until, although still steep, it has become a long, retreating slope instead of a precipice. On the north side of the river here and for about one and one-fourth miles to the eastward, no glacial débris is discernible such as could be classed as morainal. The bare cliff faces afford no place for its lodgment; and even if once left on the more level area beside the stream, it has been either washed away or covered by irregular heaps of talus which have fallen since the ice withdrew.

On the south side, however, the longer, less steep canyon wall has allowed the glacial débris to remain in sufficient quantity to mark the approximate position of the edge of the ice at the time of its farthest advance. The débris consists of bowlders in variety, some with characteristic glacial striae, exposed at various points along the boundary as mapped and to the east of this line. In sharp contrast, the slope to the west of the boundary is covered by black soil, usually with few rock fragments, or, where they exist, consisting almost entirely of fragments of bed rock.

Between Bilk Creek and Lake Fork the south wall of the canyon becomes somewhat steeper; in the upper 200 or 300 feet, however, the slope affords lodgment for drift, forming a well-marked narrow shelf for a distance of more than a fourth of a mile. The top of the mesa to the south is entirely covered with drift to a depth which at its maximum may reach 200 or 300 feet. On the north side of the canyon, the wall is still precipitous, with no possibility for the lodgment of drift; but at a point opposite the railroad bridge over the San Miguel River, drift appears on the edge of the

mesa at an elevation of 9,000 feet, or about 1,000 feet above the stream. This drift consists of a narrow, thin sheet of glacial débris, with bowlders of granite and diorite-monzonite, some of them striated, mingled with a much larger number of sandstone bowlders and fragments which cannot be distinguished from the Dakota sandstone, which here forms the bed rock. Opposite the mouth of Lake Fork the drift is found farther north, covering an area which suggests a lobelike expansion of the border of the ice up the valley of the small tributary which enters from the north, and over the low divide northwestward into the upper part of the valley of a tributary of Deep Creek. At the point on the eastern side of the lobelike expansion, where the boundary of the drift returns to the edge of the canyon, a well-marked morainal ridge occurs. It has a length of about 20 rods, a height in some places of as much as 30 feet, and contains bowlders in variety up to five feet in diameter, some of them showing striations. Eastward from this morainal ridge the boundary of the drift leaves the top of the mesa, descending rapidly some 300 feet over the still steep canyon wall toward the conspicuous moraines which partially fill the valley of the San Miguel in the vicinity of Keystone.

The moraines below Keystone are formed from material brought partly by ice advancing down Lake Fork, partly by that coming down the main valley from the east. San Juan bowlders up to 15 feet or more in diameter characterize the drift from the east; granite or diorite-monzonite in bowlders up to about 3 feet in diameter, that from the south. The mesa lying in the angle between the main valley and Lake Fork is covered with drift brought from the south; this drift extends eastward more than half a mile from the nearly perpendicular rock face which at this point forms the upper part of the east wall of the canyon of Lake Fork. While there is more or less commingling of drift from the two sources, yet, speaking generally, the small tributary of the San Miguel River, which enters from the south about one mile east of Lake Fork is the dividing line between drift from the east and from the south. Half a mile west of this tributary and between the railroad and the San Miguel River, the moraines take the form of low ridges extending in a northeast-southwesterly direction. On the north side of the

river, and extending one-fourth to one-half a mile up the valley from this point, are glacial deposits which are being treated by hydraulic process to recover the gold they contain. These deposits, as well as those extending eastward for half a mile from the small tributary referred to, and lying chiefly on the south side of the river, show in places layers of stratified silt, sand, and gravel; the greater part of the deposit, however, is unstratified.

The drift in the vicinity of Keystone constitutes by far the largest accumulation of glacial débris to be found in the canyon of the San Miguel; judging from the comparatively small number of large San Juan bowlders found farther down the canyon, the Keystone drift is in the nature of a terminal moraine for the glacier which advanced from the east. On August 1, 1904, drift in the form of a ridge transverse to the stream at a point about four-fifths of a mile east of the mouth of Lake Fork was being washed down in the process of hydraulic mining; the work showed that the pre-glacial channel of the San Miguel River at this point was about 100 yards farther north than at present, and approximately parallel to its present course, and that the pre-glacial channel had a depth of bed as much as 30 feet lower than the bottom of the present channel. It appears, therefore, that the pre-glacial channel was filled to such an extent as to displace the stream and cause it to flow at a higher level along the south wall of the valley where it has in post-glacial time eroded a new channel not more than 10 to 20 feet in depth.

This accumulation of drift in the vicinity of Keystone is believed to have been chiefly responsible for the existence of a glacial lake which extended eastward from Keystone to a point beyond the city of Telluride, a distance of more than four miles; and as the greater part of this drift for a quarter of a mile or more below the mouth of Remine Creek contains numerous large San Juan bowlders, the drift chiefly responsible for the existence of the lake must have been brought by glaciers from the east. The date of this glacial lake is therefore fixed for the time just following the retreat of the ice up the San Miguel valley after depositing the drift at and below the mouth of Remine Creek. The silting-up of this lake has produced a flat-bottomed, comparatively level valley, as shown in Fig. 3. The surface of this valley is now about 400 feet higher than the

bottom of the pre-glacial channel of the San Miguel River exposed in the process of hydraulic mining below Keystone as referred to above.

In addition to the drift near Keystone, deposits distinctly morainal in character occur at two other points in the bottom of the valley. One of these points is between one-fourth and one-half a mile eastward from the mouth of Remine Creek; the other, just east of Eder Creek. Both of these accumulations are to be regarded as small recessional moraines. The westernmost one consists of almost bare, rounded hillocks about 60 feet higher than the level valley floor to the east, and with slopes of 25° or 30°; these hillocks constitute a narrow, but irregular belt across the valley somewhat convex downstream. The drift here consists of bowlders up to 6 feet in diameter, some of which are well striated, mingled with sand and clay. The varieties of rock present include Telluride conglomerate, quartzite and granite such as are contained in the Telluride conglomerate, sandstone both light-colored and red, and bowlders of the San Juan formation. Between this belt and the much higher, forest-covered morainal accumulation lying farther west than the mouth of Remine Creek, there is a depressed area occupied in part by ponds due to dams constructed by the Keystone Hydraulic Mining Company (Fig. 4). The second recessional moraine lying just east of Eder Creek consists of a much narrower, broken series of hillocks, likewise convex downstream. These hillocks are not more than 10 to 20 feet higher than the general level of the valley bottom. Like the first recessional moraine described, this one has bowlders in variety; but here, with the exception of San Juan bowlders up to 10 feet in diameter, they are small.

Lateral moraines along the San Miguel valley—south side.—From the low recessional moraine which lies east of the mouth of Remine Creek, a ridge of glacial drift extends eastward on the south side of the valley to Prospect Creek, a distance of half a mile. This ridge has an elevation of about 70 feet above the surface of the lacustrine plain forming the bottom of the valley, a height of crest above the depression to the south of not more than 20 feet at any point, and a width of from 10 to 150 feet. This ridge constitutes the only well-marked lateral moraine belonging to the late recessional stages of ice in the San Miguel valley.

Well-marked ridges or benches of glacial material corresponding in elevation to the upper parts of the drift accumulation near Keystone occur on the south side of the valley as follows:

1. Near Telluride, three-quarters of a mile west of Bear Creek. A small stream here enters the valley of the San Miguel from the south, and the moraine lies at an elevation of 9,750 feet across the mouth of the basin drained by this stream. The moraine is here a

FIG. 4.—Recessional moraine (in center), in the valley of the San Miguel River about a half-mile east of the mouth of Remine Creek. Water in depression to left is held by a dam. Elevation about 8,600 feet.

well-marked ridge, and stands 30 to 40 feet higher than the surface of the basin just back of it. In composition the ridge is made up of a variety of rocks: San Juan, Telluride conglomerate, light-colored sandstone, and an occasional piece of Dolores sandstone. Striated bowlders were found at the point where the stream has cut through the moraine. The total length of the well-marked ridge is something less than 80 rods. An effort was made a few years ago

to make a reservoir of the basin lying back of this ridge by filling up the stream-cut in the moraine; the dam thus formed has been largely washed away, but the name, the "Van Atta dam," is still used to refer to the part remaining. Below the moraine to the north, are two or three secondary ridges or benches, the one most plainly marked being about 250 feet below the principal ridge, that is, at an elevation of about 9,500 feet. From these ridges glacial drift covers the valley slope down to the river, nearly 1,000 feet below; bowlders up to 8 feet in diameter occur here.

2. A half-mile farther west another small tributary enters the San Miguel River from the south. The moraine here is not a well-marked ridge, but a level bench across the valley, showing sections of typical morainal débris.

3. From the point just named westward the moraine cannot be distinguished for about a mile and a half. The slope of the valley is steep, covered with a forest of spruce and aspen, and shows occasional outcrops of rock in place; little glacial débris could remain on this slope. But at a point about one-fourth of a mile east of the road which leads from the village of San Miguel up the south slope of the San Miguel valley, glacial drift appears in abundance at an elevation of about 9,550 feet on the crest of the ridge which divides the San Miguel valley from the valley of Prospect Creek, and continues as a well-marked ridge from this point westward to the deposits near Keystone. At the point where the road mentioned above crosses this ridge there is a notch some 50 feet or more in depth. Small, but distinct ridges of clay, gravel, and small bowlders lead off from the vicinity of this notch in a southwesterly direction toward the valley of a tributary of Prospect Creek. West of the notch referred to for half a mile or more the moraine consists of two distinct ridges or crests; the crests are never far apart, making thus a single ridge with a double crest rather than two separate ridges. The lower crest is always to the north, being from 50 to 100 feet lower than the other.

Through this double-crested lateral moraine Prospect Creek has cut a channel sufficiently deep to allow its basin to be drained, though it still lacks over 350 feet of having cut down to the level of the San Miguel River. The sides of the cut are steep where the

stream crosses the lower ridge of the moraine, exposing unassorted glacial drift with bowlders in variety, ranging in size for the San Juan bowlders up to nearly 20 feet in diameter; the depth of the cut is here about 50 feet. Where the stream crosses the higher ridge of the moraine the cut is comparatively broad, and about 150 feet deep. The area south of the moraine at this point shows some effects of ponded waters; the topography, however, is not such as is due to the silting-up of a lake; it is rather that of a flood-plain which has been somewhat eroded.

West of Prospect Creek gap the topography is not so simple as to the east. The lower ridge persists, but the higher one flattens out southward into a series of gentle swells, and finally joins a higher point west of the road which leads from Keystone up to the plateau to the southeast. This arrangement of the drift, together with the sharp turn that Prospect Creek makes to the northward just at the gap, indicates that the valley of Prospect Creek extended on to the northwest in pre-glacial time, joining the valley of the San Miguel River probably somewhere near Keystone.

Lateral moraines along the San Miguel valley—north side.—The most easterly point at which the lateral moraine is to be found on the north side of the valley is on the west side of Royal Gulch at an elevation of about 10,000 feet. The cut made by the road at this point has exposed a heterogeneous mixture of clay and bowlders, the latter chiefly from the San Juan and Telluride formations; some of the bowlders are striated. The amount of this deposit is comparatively small; that part deserving mention as decidedly morainic is included within a distance of less than 40 rods along the side of the valley.

Farther west, a short ridge of glacial drift occurs on the east side of Cornet Creek at an elevation of 9,800 feet, and on the east side of Butcher Creek at 9,650 feet, extending in each case from the eastern side of the valley to the stream channel, and rising 50 to 60 feet higher than the somewhat flattened area just to the north.

At the junction of the valley of Mill Creek with the San Miguel, no morainic ridge appears such as is found in the valleys of Cornet Creek and Butcher Creek. The ice from Mill Creek basin evidently had sufficient force to push out into the valley of the San

Miguel any débris which the glacier in the latter may have carried at its margin. On the west side of Mill Creek a morainic ridge extends in a direction south of west from an elevation of 9,500 feet down to about 9,100 feet; but this ridge is probably chiefly due to ice from Mill Creek rather than to that coming down the San Miguel valley.

No further remnants of a lateral moraine occur on the north side of the San Miguel valley until a point is reached about three-fourths of a mile east of Remine Creek at an elevation of 9,500 feet; beginning here, glacial débris forms the top of the ridge extending south of west to Remine Creek. At its eastern end this ridge is not so well marked as the moraine on the south side of the valley; farther west the ridge is more pronounced. One noticeable feature of this part of the moraine is the number of large bowlders which lie upon its southern slope. The elevation of the east end of this ridge, 9,500 feet, is about 300 feet higher than the crest of the lateral moraine on the opposite side of the San Miguel valley. This difference in elevation is probably the result of the change in direction of the course of the valley of the San Miguel. It will be noticed that at a point about halfway between Eder Creek and Remine Creek, the San Miguel River changes its course from north of west to south of west, a change of about 25°. The ice having motion in a north-of-west direction before reaching this point would not change its direction of movement readily, and so would crowd up on the north side just below the point in the valley where the change of course takes place.

Striae and striated bowlders in the San Miguel valley.—Striated bowlders occur in abundance in the drift in the San Miguel valley, both in the moraines near Keystone, and at practically all points farther east where there is any considerable accumulation of glacial débris.

Striae on rock in place were observed at three different locations, all on the north side of the valley; in each place a part of the striae are on a rock face of steep slope, and show dip in an upstream direction. This upstream dip is interpreted as being the result of the crowding-up of the glacier on the north side of the valley, due to the force of the ice entering from two southern tributaries, viz.,

Bear Creek and Bridal Veil Creek. The points observed and the measurements made are as follows:

1. At several points near the Old Smuggler Mill, near Marshall Creek. In one area, 60 feet above the mill at an elevation of 9,300 feet, the rock face forming the side of the valley has a slope of about 40°; the striae dip up the valley (eastward) 15° to 17°. In another area, 150 feet to the west, the dip up the valley is from 3° to 5°. The direction of the striae varies from N. 52° W. to S. 88° W.

2. One-fourth of a mile east of Owl Gulch at an elevation of 9,400 feet (500 feet above the bottom of the valley), sandstone forming the side of the valley has a slope of face of 60°; striae dip up the valley (eastward) 10°. Direction of striae about N. 87° W.

3. About one-fourth of a mile east of Owl Gulch at an elevation of 9,000 feet, a small reservoir has been constructed with a ledge of red sandstone for its bottom. At some places the sandstone exposes nearly vertical faces, and on such faces some of the striae have a dip up the valley of about 5°. Some of the striae on these faces have an equal or greater degree of dip down the valley; but there are a greater number of striae exposed which dip up the valley than down the valley. Striae here vary in direction from S. 63° W. to N. 78° W.

Thickness of glacial ice in the San Miguel valley.—In the cirque-like head of the San Miguel valley, two miles east of Telluride, the ice was probably not less than 1,500 feet in maximum thickness. In the neighborhood of Telluride, the maximum was about 1,000 feet, the thickness gradually decreasing westward to the neighborhood of Keystone.

VALLEY OF EDER CREEK

Ice of the more recent epoch filled the main valley of Eder Creek and extended to the edge of the glacier which moved down the valley of the San Miguel. The head of the valley is an excellent example of a glacial cirque. At the sides and head are long talus slopes with precipitous rock walls in places above them; on the bottom the talus fragments have been pushed into the successive ridges characteristic of rock streams.

A precipitous rock face at an elevation between 10,500 and

11,000 feet separates the cirque from the forest-covered portion of the valley below. Below the precipice, well-developed lateral moraines extend on either side of the valley down to about 10,000 feet in elevation. Below this point to the edge of the valley of the San Miguel, a distance of nearly a mile, the morainal deposits consist of an irregular grouping of hillocks, with a few fragments of ridges transverse to the valley. From the abundance of the moraines in the lower part of the valley, and from their arrangement partly as ground moraine and partly as recessional moraines, it seems probable that but little ice from the valley of Eder Creek was added to the glacier in the San Miguel valley.

In the valley of the east fork of Eder Creek, a glacier less than a mile in length existed in the later stage of glaciation. Above 11,000 feet in elevation the valley shows the rounded forms due to the effect of passing ice wherever rock in place outcrops in projecting ledges or points; back of the more level, rounded slopes are the precipitous faces of the bounding walls, with steep talus slopes, overgrown, in this valley, for the most part with scanty vegetation. Between 10,500 and 11,000 feet in elevation, the stream draining this tributary valley has a very steep-walled, V-shaped channel. In the bottom of the channel, and at some places for 10 feet to 20 feet up the sides, the Telluride formation outcrops; lying on the Telluride formation is glacial débris 30 to 40 feet thick, containing bowlders up to 4 feet in diameter, some of which are well striated.

The thickness of the ice in the valley of Eder Creek does not seem to have exceeded a maximum of 200 to 300 feet.

VALLEY OF MILL CREEK

The main valley of Mill Creek, heading south of Gilpin Peak, is broadly U-shaped above about 10,500 feet in elevation, becoming broader toward the upper end. Knobs of rock in place at frequent intervals show the rounded surfaces of *roches moutonnées*, but in most places no striae could be found. The surface is weathered rough, or broken up, as if by changes of temperature, into small fragments. Grooves are found at about 11,100 feet elevation on the left bank of the stream, with direction S. 43° W. In the bottom of the valley some areas are almost flat; at a few points in

the upper part small ponds occur. Two rock streams occur at from 12,000 to 12,500 feet in elevation. Talus slopes and precipitous cliffs beyond the talus mark the boundary of the cirquelike valley.

The tributary valley from the northwest has a bottom with rounded ledges; but the stream is in a deep canyon part of the way, first at a point more than halfway up the valley and again near its mouth. No striated rock surfaces were observed. In general, the slope of the bottom of the valley is very steep, and the sides are made up of long talus slopes with precipitous faces above them. At the upper end of the valley is an unusually fine example of a rock stream, which extends more than a quarter of a mile from the precipice which forms the head of the valley. In the lower part of the valley of this tributary on the west side, at an elevation of about 11,200 feet, is a small area of uneven, hummocky ground inclosing a pond 30 or 40 feet in diameter; this uneven topography is evidently due to landsliding.

At an elevation of about 10,300 feet, a precipitous cliff of the Telluride formation causes falls 100 feet or more in height in the streams both from the head of the main valley and from the branch coming from the northwest. Below the falls and down to about 9,900 feet in elevation there is much fragmental material in the stream bed, rock in place being visible only occasionally. At about 9,900 feet, the stream bed lies in a canyon cut in Dakota sandstone. Again at from 9,200 to 9,400 feet in elevation there are many bowlders along the stream. At most other places, the stream has its channel in bed rock or nearly so.

Park Basin is very similar in its main features to the valley tributary to Mill Creek from the northwest. It has a steep gradient where it joins the main valley, a grade less steep from 11,000 to 12,000 feet in elevation, steep talus slopes, and precipitous cliffs beyond the talus.

On the west side of the main stream at an elevation of from 10,000 to 10,200 feet, is an area of irregular, hummocky topography, in which are some small undrained basins. The material here is clay, with pebbles and bowlders, some of which are rounded. This area clearly lies within the limits of glaciation for this valley, but the uneven topography is no doubt due largely to landsliding.

On the west side of Mill Creek where it joins the valley of the San Miguel, a short, well-defined ridge extends south of west nearly to Eder Creek. Near its upper end its crest is about 500 feet above the bed of the stream (Mill Creek), and rapidly decreases in elevation toward the southwest. On the side of this ridge away from Mill Creek its slope is short, and joins, in its upper part, the unglaciated slope of the ridge lying between Mill Creek and Eder Creek; farther down it joins the glacial débris of the main (San Miguel) valley. No ridges transverse to Mill Creek appear in connection with the lateral moraine; either no terminal moraine was formed by the glacier occupying the valley of Mill Creek, or, if formed, it has been carried away.

Upstream from the lateral moraine just referred to, one-fourth to one-half a mile from where Mill Creek enters the San Miguel valley, there is an accumulation of glacial débris lying near the stream and up to about 9,400 feet in elevation. This accumulation forms what appears when viewed from the upstream side to be an irregular, narrow terrace whose top is not more than 100 to 150 feet above stream. Above the accumulation, the valley becomes slightly broader and for about one-fourth of a mile is sufficiently level to indicate that ponding of water with accompanying silting-up must have taken place. This more level surface is in sharp contrast with the steep slope on the same side of the stream near the San Miguel valley. On the east side of Mill Creek, no terrace appears corresponding to that on the west; some glacial débris is present, however. This deposit of drift at 9,300 to 9,400 feet in elevation is interpreted as a recessional moraine which for a time partially dammed the stream.

The maximum thickness of ice in the valley of Mill Creek was probably from 500 to 800 feet.

VALLEY OF CORNET CREEK

The head of this valley is a cirque with precipitous walls, steep talus slopes, a bottom showing some rock in place, some loose bowlders, and some finer fragmental material which in places supports a sufficient growth of low plants to conceal the rock fragments under a covering of green. The tributary valley from

the east, lying southwest of Mendota Peak, has much talus, a larger proportion of its area supporting vegetation, and lacks the high steep walls at its head which are characteristic of a typical cirque.

From timber line, about 11,000 feet in elevation, down to 10,200 feet, a considerable growth of trees, with the accompanying products of vegetable decay covering the ground, obscures the underlying rock in many places; a number of outcrops were found, however, yet no striae were seen.

On the east side of the valley, beginning at an elevation of about 10,200 feet and extending in a southerly direction for about one-fourth of a mile, is a distinct ridge composed, so far as could be observed, of clay, pebbles, and rounded bowlders, some of which are striated. This ridge begins just below a well-rounded ledge of the Telluride formation, and extends to the stream which joins Cornet Creek from the east on the 9,800-foot contour line.

The moraine lying across the lower part of the valley and forming part of the lateral moraine on the north side of the San Miguel valley has already been referred to. North of this moraine for nearly a mile the bottom of the valley has in most places a covering of glacial drift, part of which is stratified and part unstratified. On the west side of Cornet Creek opposite the moraine at 9,800 feet elevation, bowlders and other glacial débris lie as much as 100 feet higher than the top of the moraine on the east side. This fact probably has its explanation in the crowding-up of the glacier on the west side of Cornet Creek due to the ice coming from the valley of Bear Creek, a tributary which enters the San Miguel valley from the south at a point nearly a mile farther upstream than the valley of Cornet Creek.

The general shape of the different parts of the valley is typical of that usually found in the small, high, glaciated valleys of this region; that is, an upper portion comparatively broad and flat-bottomed, bounded by talus slopes and precipitous cliffs, and a lower part, narrower, with steep sides, gradually changing in shape of cross-section from U-shaped to V-shaped, as the tributary approaches the main stream. The maximum thickness of ice in the valley probably did not exceed 500 feet.

VALLEY OF MARSHALL CREEK

Marshall Creek drains Marshall basin and Middle basin, lying in the Telluride quadrangle, and Savage basin lying for the most part in the Silverton quadrangle. All these basins, as well as the valley of Marshall Creek below, are practically free from glacial débris; except for accumulations of talus and rock streams, rock in place is everywhere at the surface. *Roches moutonnées* occur at many points, and striae are abundant, their direction coinciding in general with the direction of the stream courses. Special illustrations of *roches moutonnées* may be mentioned as follows:

1. In the northwest part of Marshall basin, beginning at an elevation of 12,400 feet and including an area one-fourth of a mile square below that elevation, many *roches moutonnées* occur; striae within this area have directions varying from S. 25° E. to S. 35° E.

2. At an elevation of 11,300 feet on the north side of the road near the turn from northwest to west, two sets of striae are plainly marked; one set has direction S. 5° to 10° W.; the other set, not so deeply cut, about S. 45° W.

In the upper part of the basin the western slope is covered by a long talus slope, completely concealing the rock in place on that side. In the northeast part, at an elevation of from 12,500 to 12,800 feet, is a small rock stream.

In Middle basin a shallow lake occupies a rock basin; the outflowing stream passes through a channel about 10 feet deep. Northwest of the lake a ledge of rock in place 100 feet high shows *roches moutonnées*, but no striae. A little higher, at an elevation of nearly 11,700 feet, in both the east and the west branches of Middle basin rock streams are found extending from the base of the talus slopes which lie at the foot of the precipitous bounding walls of the valley. These rock streams are of two periods; the more recent are composed of fragments fresh in appearance, angular, and bare except for lichens on some of the surfaces. The older lie at the lower or outer edge of the more recent, the rock fragments are much disintegrated, so that the crests of the ridges are less sharp, and soil enough has accumulated to support vegetation, making the surface appearance that of rounded, green hills instead of bare ridges of angular fragments.

In Savage basin above 12,000 feet in elevation, there are found usually rock streams, and talus slopes at the bases of the precipitous bounding walls; below this elevation, as in the case of Marshall and Middle basins, there is usually a rock floor with *roches moutonnées* and numerous striae; unlike Marshall basin, however, Savage basin has a number of small rock basins, some of which contain water. The rock streams here are of two periods, as is the case in Middle basin, and the arrangement of the two with respect to each other is likewise for the most part the same, that is, the older lying as a narrow belt outside or below the more recent. In a few places, however, the older, more rounded slopes are farther up the valley than those made up of bare, angular rock fragments; this seems to be due to the movement of the fragments transported in more recent time around the older deposit, much in the way that a glacier is seen to move around an island or a promontory of rock which is a little too large to be overridden.

The maximum thickness of ice for the area drained by Marshall Creek was probably about 800 feet.

VALLEY OF INGRAM CREEK

The greater part of the area drained by Ingram Creek lies in the Silverton quadrangle. The north branch of the basin has but few good examples of *roches moutonnées*, though many projecting points and ledges are distinctly rounded. Striae bearing S. 88° W. occur on the east side of the stream at an elevation of 12,000 feet. In the upper part of the north branch are the usual precipitous bounding walls, talus slopes, and rock streams of two different periods.

The central subdivision of the basin is deeply carved. Channels up to 100 feet wide and 50 feet deep occur in the bed rock, approximately parallel to the length of the valley; the sides of these channels are precipitous, and in many places well smoothed. Striae in general parallel to the course of the stream are abundant. Talus slopes are found at the north side and the east end.

The south branch has many *roches moutonnées;* some of the surfaces are striated, some are weathered rough. Ice passed over the 12,400-foot ridge situated between the central and south

branches of the basin. In the southeast part of the south branch the *roches moutonnées* forming the bottom of the basin are not more than 300 feet lower than the steep-sided ridge which forms the divide between Ingram basin and Mineral basin; it is therefore believed that the upper surface of the glaciers occupying these two basins was continuous at the time of the maximum extent of ice in the more recent epoch of glaciation.

The lower part of the course of Ingram Creek as named on the Telluride topographic sheet is an extension of the upper part of the valley of the San Miguel River. From about 11,000 feet in elevation, the stream descends in a series of falls and cataracts to its junction with Bridal Veil Creek, a total fall of over 1,500 feet in about seven-tenths of a mile. Immediately above elevation 11,000 feet, the valley has the U-shaped cross-section. At a higher elevation it assumes the form common to the high glaciated valleys in this region. The maximum thickness of ice in this valley was probably about 500 feet.

ON THE STRATIGRAPHIC POSITION AND AGE OF THE JUDITH RIVER FORMATION

A. C. PEALE[1]

For some years there has been a suspicion in the mind of the writer that perhaps, after all, the older geologists were correct in their views as to the position of the Judith River beds in their relation to the previously recognized, undisputed Fort Union formation, i.e., that the Judith River beds were immediately below the Fort Union formation. This view was strengthened when, in 1909, plants of undoubted Fort Union age were brought in from supposed "Judith River beds" on Big Sandy Creek, about fifty miles northwest of the mouth of the Judith River, by members of the U.S. Geological Survey, and confirmed upon a careful study and review of the evidence furnished by stratigraphic, vertebrate, and invertebrate data as detailed by Stanton and Hatcher in their work[2] and by Dr. O. P. Hay's paper "Where Do the Lance Creek (Ceratops) Beds Belong?"[3] It is the purpose of the present paper to show that the Judith River beds are of Eocene-Tertiary age, and not of Belly River (Cretaceous) age, and are to be correlated with the Lower or somber portion of the Fort Union formation as defined and described by Knowlton,[4] now known as the Lance formation.

Nearly forty years ago, or, to be more exact, in 1875,[5] the writer, in attempting to correlate the Cretaceous and Tertiary formations in connection with work of the Hayden Survey in Colorado, took up the consideration of the Judith River beds, and among other

[1] Published by permission of the secretary of the Smithsonian Institution.

[2] *Bull. U.S. Geol. Surv., No. 257,* 1905.

[3] *Proc. Indiana Acad. Sci.*, Twenty-fifth Anniversary Meeting, 1909.

[4] The "Stratigraphic relation and paleontology of the 'Hell Creek beds,' 'Ceratops beds,' and equivalents, and their relation to the Fort Union formation."—*Proc. Wash. Acad. Sci.*, XI, No. 3, pp. 179–238.

[5] *U.S. Geol. and Geog. Surv. Terr., 1874,* Washington, 1875, pp 154, 155.

conclusions, made the statement that the Judith River beds lie immediately below the Fort Union (as then known), and have their equivalent in Colorado, occupying there the same position as in Montana. He also stated that he believed them to be of Cretaceous age, and thought that they formed either the upper part of the Fox Hills, or a group to be called No. 6, the Fox Hills being known as No. 5.

This opinion as to the Cretaceous age of the beds was based upon the study of the vertebrates by Professor E. D. Cope, a position which has been taken by all vertebrate paleontologists, both in the United States and in Canada. From this opinion the writer, in the light of what is known today, which will be briefly detailed below, dissents, and wishes to express here the conviction that the Judith River beds are of Eocene age. He, however, holds to his previous view that they do lie between the Fox Hills and the Fort Union formations as then known and described. This is why they were so generally referred to the Laramie. This is the position that has been assigned them by everyone who has studied them from the time they were first noted by Hayden in 1853–55, and named by him in 1871, down to the time of the investigations by Hatcher, who was the first (in 1902)[1] to assign them to a position in the Montana Cretaceous lower than that of the Fox Hills. In 1896, however, Hatcher had considered the Judith River beds as representing the lower 400 feet of strata at the base of the Ceratops beds of Converse County, Wyo., and just above the Fox Hills sandstone. This position above the Fox Hills coincides with that assigned them by Hayden, Meek, Cope, and Osborne, and by the writer, as just stated. The position indicated for the beds by Hatcher, in 1902,[2] is that assigned them by Stanton and Hatcher in 1905, and their views are fully elaborated in their bulletin[3] published by the U.S. Geological Survey.

The historical aspect of this question has been so thoroughly and most admirably stated by Stanton and Hatcher in the bulletin just cited, and it is only necessary to recapitulate enough to show that the statement made above is correct.

[1] *Science*, XVI, 831, 2.

[2] *Ibid.*, XVIII, 211.

[3] *Bull. U.S. Geol. Surv., No. 257*, 1905.

In 1861 Meek and Hayden, after referring to the early conflicting views as to the age of the Judith River beds, say:[1] "They are really of Tertiary age, and hold a position at the base of the great lignite series [Fort Union formation] of the northwest." In 1871[2] Hayden gave these deposits the name "Judith group," and says:

> The sediments do not differ materially from those of the Fort Union group, and they contain impure beds of lignite, fresh-water mollusca, and a few leaves of deciduous trees. But the most remarkable feature of this group is the number and variety of the curious reptilian remains of which we have only yet caught a glimpse.

As to the age of the underlying sandstones near the mouth of the Judith River, concerning which there had previously been some doubt, both Meek[3] and Hayden[4] in 1875, independently of each other, correlated them with the Fox Hills, Meek saying that "we cannot be far wrong in regarding the latter beds [the marine Cretaceous beds at the mouth of Judith River] as holding a position at the horizon of the top of the Fox Hills." Cope,[5] in 1874, in a "review of the vertebrata of the Cretaceous period found west of the Mississippi River," in a notice of the Judith River beds under the head of the Fort Union or lignite group, says: "From the standpoint of the writer, these beds would be at the top of the Cretaceous and more or less related to the Fort Union epoch." After the early explorations by Hayden, the first geological examination of the Judith River country was made by Edward S. Dana and George B. Grinnell[6] in the summer of 1875. They made a short excursion to the mouth of the Judith River and spent two days in this locality. They speak of their results being, of course, meager. "Enough,[7] however, was seen to establish the age of the beds at this point as beyond a doubt Cretaceous, three members of this division of Meso-

[1] *Proc. Acad. Nat. Sci.*, 1861, p. 415, footnote.

[2] F. E. Hayden, *Preliminary Report, U.S. Geol. Surv. Wyoming*, Washington, 1871, p. 97.

[3] *Bull. U.S. Geol. and Geog. Surv.*, I, 2d series, No. 1, p. 39.

[4] *Ibid.*, p. 403.

[5] *Bull. U.S. Geol. and Geog. Surv., 1874–75*, I (1875), 1st series, p. 6.

[6] Geological report in Ludlow's report of a *Reconnaissance from Carroll, Montana, on the Upper Missouri, to the Yellowstone National Park and Return*, Washington, 1876.

[7] *Ibid.*, p. 124.

zoic time having been found there and identified by fossils." The three members referred to were No. 4, Fort Pierre, No. 5, Fox Hills, and No. 6, Fort Union. The thickness of the latter was estimated at 400 feet, and the strata are described as beds of white sandstone containing occasional layers of a clayey brown sand rock, "at the mouth of the Judith River, evidently overlying the beds of No. 5 [Fox Hills] before referred to." From these beds they obtained the vertebrae and long neck bones of dinosaurs identified by Professor Marsh as belonging very near the genus *Hadrosaurus* [Trachodon] of Leidy. With these remains were found Unios and, in some layers, a little lignite, the general association seeming to refer the deposits to the Fort Union beds.

Professor E. D. Cope was the next to visit the region. In the summer of 1876 he explored the region near the mouth of the Judith River and eastward as far as Armel's Creek, 130 to 150 miles to the eastward from Fort Benton. He fully corroborated Hayden's observations and his sections are substantially the same. He regarded the Judith River beds as Cretaceous, with Tertiary affinities,[1] and referring to their position, says:[2] "In the Judith region the relation of the Fox Hills sandstone to the superincumbent strata is everywhere observable." "The ferruginous, soft sandstone of the Fox Hills group is everywhere the line of demarkation between the black shales of No. 4 [Fort Pierre] below and the Judith River beds above."[3]

The last identification of fossils made by Professor F. B. Meek was for Professor Cope. The fossils were *Inoceramus barabini*, *Inoceramus* sp.; and *Baculites compressus*, and were obtained by Cope[4] from the black shales of No. 4. Although Meek had not revisited this region, his last word on the Judith River beds is interesting and illuminating.[5] Basing his opinion upon the invertebrates found in the beds immediately underlying the Judith River beds near the mouth of the Judith River, he correlates them with the upper part of the Fox Hills.[6] As to the Judith River group,

[1] *Bull. U.S. Geol. and Geog. Surv.*, III (1877), 569.

[2] *Ibid.*, p. 568. [3] *Ibid.* [4] *Ibid.*

[5] *Report of U.S. Geol. Surv. Terr.*, IX (1876).

[6] *Ibid.*, p. xxxvi.

which he believes to be somewhat extended in the upper Missouri River region at the base of the Fort Union group, he suggests the probability of its Cretaceous age, but says: "Yet this can scarcely be properly regarded as an established fact,"[1] and then refers to the mingling of the Eocene and Cretaceous types of vertebrates in the beds.

During the summer of 1882 Dr. C. A. White[2] made a special study of the geology about Fort Union and the region extending thence up the Yellowstone. He ascertained as the result of this study that, with the exception of one or two small exposures of the Fox Hills lying immediately below the Fort Union [which he referred to the Laramie], the latter occupied the whole region and from the beds so referred the collected fossil plants, fresh-water invertebrates, and dinosaurian remains, and states that the latter are found toward the base [that is, in the beds since referred to the Lance formation].

The following year Dr. White[3] spent part of the months of July and August in the area between Fort Benton and Judith River and the Highwood Mountains studying the relations of the Laramie [Lance ?] group to the underlying formations. He was joined here by Professor L. F. Ward[4] and on August 22 they began the descent of the Missouri from Fort Benton to Bismarck, which they reached September 21. Ward says that the most notable fossil plant locality discovered was about 7 miles below Coal Banks on the right bank of the Missouri River, occupying a stratigraphic position near the base of the Fox Hills, probably in the Fort Pierre group. These were of special interest as being the only Cretaceous fossil plants found up to that time in the United States above the Dakota group. White and Ward as the result of this trip saw no reason to differ with the latest conclusions of Meek and Hayden, or those of Cope, but, as Dr. Stanton[5] says, their stratigraphic observations were never fully published. Later, White[6] in dis-

[1] *Ibid.*, p. l–li.

[2] *Am. Jour. Sci.*, 3d ser., xxvii (1883), 121.

[3] *Fifth Ann. Rept. U.S. Geol. Surv. for 1883–84–85*, p. 50.

[4] *Ibid.*, p. 60.

[5] *Bull. U.S. Geol. Surv. No. 257*, p. 27.

[6] *Ibid.*, *No. 82*, pp. 174–77.

cussing the Belly River formation, refers to the identity or close resemblance between the Belly River beds and the fresh-water Laramie [Lance] (which included at that time the Judith River beds) and suggests the gradual coming-in of the Belly River series between the Colorado and Montana, and the gradual thinning-out of the Montana until the Laramie [Lance] occurs, resting immediately upon the Belly River, the two blending, with the Montana absent. He says, however: "It is true that no observation has yet been made of a complete thinning-out of the Belly River formation in any direction, nor of its blending with the Laramie [Lance] by the absence or by the thinning-out of the Montana formation."[1]

Dr. White[2] recognized the fact that both the Belly River series and the Laramie [which as he used it included the Lance and the Judith River beds] rest upon marine Cretaceous and says also: "Unlike the Laramie [Lance], the Belly River formation is immediately overlain, as well as underlain by marine Cretaceous strata." The latter he says are undoubtedly referable to the Montana formation. He says further:[3] "What gives this formation [Belly River] especial interest is the intimate relation of its fauna and flora to those of the Laramie [Lance], although these two non-marine formations are, in the district within which both are now known to occur, separated by a great thickness of strata which are unmistakably of marine origin." Although Sir J. W. Dawson[4] has stated that the flora of the Belly River series very closely resembles that of the Lower Laramie [Lance] we shall see later on that such resemblance as exists is not very striking. In regard to the survival of the molluscan fauna he concludes that "the fresh-water habitat of the Belly River molluscan fauna was shifted by subsidence and gradual filling of aqueous areas."

In 1894 Dr. Stanton spent a few days with Mr. W. H. Weed near the mouth of Judith River. They traveled by rowboat down the Missouri River from Fort Benton to Judith, passing over and studying the formations underlying the Judith River beds, beginning with Fort Benton shales. Dr. Stanton confirmed the statements of previous observers that some of the strata beneath the Judith River beds contain a fauna that is elsewhere characteristic of the

[1] *Bull. U.S. Geol. Surv., No. 257*, p. 176. [2] *Ibid.*, p. 174. [3] *Op. cit.*, p. 175.

[4] *Trans. Roy. Soc. Canada*, III, sec. IV (1885), p. 20.

Montana group, or Fort Pierre and Fox Hills formations. He was especially impressed by the occurrence, in the upper part of these underlying beds, of a zone containing *Cardium speciosum*, *Mactra alta*, *Tancredia americana*, and other forms which in north-central Colorado are known to occur only in the Fox Hills beds immediately beneath the Laramie. No beds higher than the Judith River were seen, and the view was adopted that the Judith River series overlies all of the Montana group and is referable to the Laramie. When a few days later the overlying marine Cretaceous shales were seen in contact with upturned Judith River beds near Havre, Mont., their apparent position was supposed to be due to faulting, of which there was abundant evidence in the neighborhood.[1]

As a result of this work Dr. Stanton[2] gave Mr. Whitman Cross the following section made in Dog Creek, published in 1896:

The fresh-water Judith River beds are well exposed in bluffs on Dog Creek, 4 or 5 miles from the mouth of Judith River, and also on the north side of the Missouri within 3 or 4 miles of the same place. The section in this neighborhood shows about 650 feet of marine Cretaceous strata overlain by 300 to 350 feet of fresh-water beds. The succession of strata and thickness as estimated by Mr. W. H. Weed are as follows, beginning at the base:

1. Soft, dark clay shales.
2. Band of ferruginous sandstone with *Avicula linguiformis*, *Inoceramus cripsii*, *Baroda wyomingensis*, *Placenticeras placenta*, etc.
3. Shales like No. 1.
4. Coarse gray laminated sandstone.
5. Carbonaceous shales with bed of lignite at base 100
6. Brown sandstone with great numbers of *Cardium speciosum* and a few other species 30
7. Sandy shales 25
8. Dark clay shales with concretions containing *Baculites ovatus* in lower portion and sandy bands and concretions near the top with a characteristic Fox Hills fauna including:

Nucula sp.	Liopistha (Cymella) undata
Clisocolus cordatus	Pholadomya subventricosa
Callista nebrascensis	Mactra formosa
Tellina aequilateralis	Lunatia subcrassa
Tancredia americana	Baculites ovatus

The total thickness of this bed was not seen at any one place, but it is at least 350 feet.

Immediately above these dark shales is a bed of greenish-yellow sandstone which occasionally forms bluff exposures 50 or 60 feet high, but usually only slightly exposed in steep slopes and largely covered by wash from the softer and lighter-colored beds above. This was taken as the dividing line between

[1] Stanton and Hatcher, *Bull. U.S. Geol. Surv., No. 257*, 1905, p. 10.

[2] *Monographs U.S. Geol. Surv.*, XXVII (1896), 239–41.

the marine and fresh-water beds, though no fossils excepting silicified wood were found in the lower 200 feet of the latter. The remainder of the section, about 300 feet in thickness, is apparently conformable with the underlying beds, but is quite distinct from them in color and texture. It consists of alternations of light-colored, soft, friable sandstones, clays, and marls, with some seams of lignite and purplish carbonaceous bands. Fossils are abundant in the upper 200 feet, consisting of fragments of silicified wood, bones, and numerous invertebrates. The latter include the following species:

Sphaerium recticardinale	Goniobasis sublaevis
Sphaerium planum	Goniobasis subtortuosa
Unio danae	Goniobasis sp. closely related to G. tenuicarinata
Unio cryptorhynchus	Campeloma vetula
Anodonta propatoris	Vetrina ? obliqua
Viviparus conradi	Physa copei
Helix veternus	

At the top of the exposure above these fresh-water beds there is a band of brackish-water fossils, reported by both Meek and Hayden and by Cope, which contain *Ostrea subtrigonalis*, *Anomia* sp., *Corbicula occidentalis*, *Corbula cytheriformis*, *Goniobasis convexa*, etc. This band was not seen by me in the neighborhood of Judith River, but I afterward saw it near Havre, Mont., holding the same position above the fresh-water beds.

Cross, in commenting on this section, refers to the specific identity of the brackish-water shells found by Stanton on Dog Creek and near Havre with those found by Weed in the Livingston[1] beds, saying their presence does not indicate the Laramie (by which he means true Laramie as found in Colorado) age of the Judith River beds, and as to the apparent conformity with the Fox Hills urges for the Judith River beds the same considerations as he did in discussing the Converse County beds (now called the Lance) in Wyoming. These as given on p. 236 are as follows:

There are many places in the West where the section of visible sedimentary formations from the Cambrian to the Cretaceous seems a conformable one, and it has frequently been spoken of as such, but the researches of the last two decades have proven the existence of many important stratigraphic breaks in this series, which are in certain places shown as great unconformities but cannot be identified at other points. Especially in the plains country adjacent to the Rocky Mountains conformity of formations cannot be assumed to prove continuity of sedimentation. The visible conformity between the Ceratops

[1] The Livingston age of these beds was afterward denied by Dr. Stanton and others, but the point the writer wishes to make here relates more especially to the unconformity.

beds and the Fox Hills in Converse County cannot be accepted, contrary to other evidence, as proving the former to have been deposited in the epoch next succeeding the Fox Hills.

It is apparent from what has been quoted above that Dr. Stanton, when he went with Weed in 1894 from Fort Benton to the Judith River, found the Judith River beds in the type region in their normal position and that he was correct in assigning them to the stratigraphic position immediately overlying the Montana formation which, in its upper portions, contained a Fort Pierre and Fox Hills fauna. It was only when he got into the disturbed region near Havre, Mont., that he found marine Cretaceous shales overlying what he called "Judith River beds" and his explanation, that their apparent position *when so found* was due to faulting, was probably also correct.[1] Of course these beds exposed at Havre were not the real Judith River but the true Belly River series which normally underlies the Pierre as exposed in Canada north of this region. These beds were again examined by Dr. Stanton when with Hatcher in 1903. Their field studies were begun at this point, Milk River at Havre, and they

examined the excellent exposures along that stream to the international boundary, and beyond to Pendant d'Oreille Police Barracks, which is near one of Dawson's described localities, where the base of the Belly River beds is seen resting on the marine "lower dark shales." This is near Lake Pakowki of the maps, locally known as "Badwater Lake." We also examined the exposures of upper Belly River beds showing contact with the overlying "Pierre shales" on Sage Creek, Canada, as described by Dawson and McConnell, and continued our observations as far north as the Cypress Hills, where the top of the overlying marine Cretaceous is seen. Passing down Milk River below and around the eastern end of the Bearpaw Mountains to Cow Creek and the Missouri River at Cow Island and thence up Dog Creek, Judith, and Eagle Creek, Mont., we have studied the typical areas of the Judith River beds described by Meek and Hayden, and of the Eagle formation described by Weed. . . . .

We have become fully convinced that the Belly River beds are identical with the Judith River beds, as Dawson long ago suggested. Our conclusion

[1] Dr. Stanton's exact words are as follows: "When a few days later the overlying marine cretaceous shales were seen in contact with upturned Judith River beds near Havre, Montana, their apparent position was supposed to be due to faulting of which there was abundant evidence in the neighborhood."—*U.S. Geol. Surv. Bull., No. 257,* p. 10.

is based on lithologic character, stratigraphic sequence, the vertebrate and invertebrate faunas of the beds themselves, as well as on the paleontology of the underlying and overlying beds in both Canada and Montana.[1]

In discussing in another place[2] the areas in which Judith River beds occur, Stanton and Hatcher refer to the exposures near Havre, the eastward extent of which they did not determine, and say:

> It is very *probable* that this area is connected with the Cow Creek area by almost continuous exposures across the divide separating the drainage of the Missouri from that of Milk River east of the Bearpaw Mountains. On our journey from Havre to Cow Creek we passed through the eastern foothills of these mountains and crossed several areas of igneous rocks, but on Bean Creek near Lloyd post-office we saw outcrops apparently belonging to the Judith River beds, and *if our route had been a few miles farther east we could probably have had the formation in sight all the time.*[3]

This statement is a pure assumption, for it is evident that the beds were not traced continuously from the Milk River area to the vicinity of Cow Creek on the Missouri River, and the probabilities are that in this region to the eastward the distinction between the Belly River and the Judith River formations and not their identity would have been clearly shown. It is more than probable that here is the point where the supposed correlation fails. The Belly River, the Judith River, the Lance, and the Fort Union formations all have their representatives in this area, which is one of great disturbance due to faulting and the occurrence of volcanic intrusions. The lithological resemblance between the strata of these formations has been noted by all who have seen them, not only in this region, but to the southward and also northward in Canada. The relations of the beds in this disturbed area will be determined only after a most careful investigation of the country surrounding the Bearpaw Mountains, extending far enough away from the mountains to give normal undisturbed sections which can be closely studied. A careful stratigraphic tracing of these beds in the undisturbed region, which cannot be made in a flying trip across the country, will also be necessary, together with accurate paleontologic collections and their careful study.

[1] *Science*, N.S., XVIII (1903), 211–12.

[2] *Bull. U.S. Geol. Surv. No. 257*, 1905, p. 61.

[3] The italics in this quotation are those of the present writer.

Study by Hatcher of the vertebrate collections made by him in 1882 and 1883 from the Judith River beds led him to the conclusion that this vertebrate fauna was older than Laramie fauna of the uppermost Cretaceous. By Laramie as used by Hatcher, it must be remembered, is meant the Ceratops beds, now called the Lance formation, which in the writer's opinion has been conclusively shown by Knowlton[1] to be of Lower Fort Union (Eocene) age. Hatcher was confirmed in his views by finding marine Cretaceous shales apparently overlying the Judith River beds. It must be again recalled in this connection that this was an area of complicated folding and great disturbances, the result mainly of numerous faults recognized by all who have been in the region from the time of Hayden's first explorations to those of Hatcher and Stanton. The latter says:[2]

"No better description of the frequency of these disturbances and the difficulties they have caused the stratigrapher can be given than that of Dr. Hayden," whom he quotes. The latter part of this quotation is as follows: "So much are the beds disturbed by forces acting from beneath that it seems almost hopeless to obtain a section showing with perfect accuracy the order of superposition of the different strata."

In 1896 Hatcher made the statement that the Judith River beds were certainly older than the Ceratops beds of Converse County, Wyo., and that "the dinosaurs from the Judith River country belonged to smaller and less specialized forms than those from the latter locality," and refers in the same article to his belief that "the Judith River beds are the equivalent of the 400 feet of barren sandstones, thus lying between the base of the Ceratops beds and the marine Fox Hills sandstones in Converse County, Wyo." Later, he repeats[3] this statement and adds: "I am at present of the opinion that they pertain to a still lower horizon."

In the early part of 1903 Hatcher says he "believes the exact stratigraphical position of the Judith River beds remains unsettled and that it is premature to assert that the true Judith River beds

[1] Knowlton, *Proc. Wash. Acad. Sci.*, XI (1909), No. 3, pp. 179–238; and *Jour. Geol.*, XIX (May–June, 1911), 358–76.

[2] *Bull. U.S. Geol. Surv. No. 257*, 1905, p. 34.

[3] *Science*, N.S., XVI (November 21, 1902), 832.

certainly overlie the Fort Pierre and are of more recent age, although this is now very generally believed and may eventually prove to be the case."[1]

During the summer of 1903 Mr. Hatcher and Dr. Stanton spent two months in the field study of the Judith River formation; part of the time in the Judith basin. The results of their investigations were published in *Bulletin of the U.S. Geological Survey No. 257*, 1905. In a preliminary statement published in August, 1903,[2] they restate their belief that the Judith River beds occupy a lower position than had usually been assigned them and give a summarized section which divides the Montana into four formations in ascending order as follows: Eagle formation, Claggett formation, Judith River beds, and Bearpaw shales. As to the beds which are supposed to overlie the Judith River beds and for which the name Bearpaw shales is proposed they say:

> They have the lithologic and faunal characters of the typical Pierre but represent only a fraction of that formation as usually understood. Beneath the light-colored mostly non-marine Judith River beds, is another formation 400 feet in thickness, which in its lower half resembles the Bearpaw shales and yields a few of the same species of fossils. Its upper 200 feet, however, contain several sandstone beds which bear a fauna that has hitherto been called "Fox Hills." We propose the name *Claggett formation* for these shales and sandstones underlying the Judith River beds.

Having in mind the possibility, if not the great probability, that the two series of beds, Belly River, and the Judith River with which the former was correlated by Stanton and Hatcher, were not one and the same, but were entirely distinct formations, and that the latter is really the equivalent of the division of the Fort Union to which the name Lance has been applied by the U.S. Geological Survey, the writer decided to visit the area in which the typical Judith River beds are exposed, and in accordance with this decision the month of July, 1911, was spent in this area in company with Mr. A. C. Silberling, formerly connected with the Carnegie Institute of Pittsburgh, and Professor G. L. Wait, of the Lewistown

[1] *Science, N.S.*, XVIII (March, 1903), 472.

[2] *Ibid.*, (August 14, 1903), 211, 212. The article was sent in from the field from Judith Mountain.

High School, whose familiarity with Fergus County, Mont., was of the greatest assistance in the work. Knowing from the work of Stanton and Hatcher that the area north of the Missouri River and around the Bearpaw Mountains was one complicated in its geological structure by numerous faults and folds and areas of intrusive rocks, it was decided to begin the section far enough south so that if possible there might be no chance of error due to the occurrence of folding or faulting. We therefore followed the road leading a little west of north from Lewistown between the North and South Moccasin mountains to Deerfield, from which point we turned westward, reaching the Judith River about 40 miles above its mouth. This part of our course led us over the shales of the Colorado, as mapped by Calvert,[1] with a few outcrops of the underlying Kootenai formation showing on either side of the lower slopes of the Moccasins. The Colorado shales are well shown at Stough's ranch, having a thickness of about 1,000 feet overlaid by a sandstone referred to the Eagle. This is a massive white sandstone not over 100 feet in thickness in most places. As followed laterally it fades out into a yellowish sandstone which is somewhat shaly. This sandstone caps the bluffs on either side of Judith River, contrasting strongly with the underlying dark shales of the Colorado. Above it is an alternating series of massive yellowish sandstone and shaly beds reaching a total thickness of about 200 feet. A coal mine is worked in these upper sandstones about 2 or 3 miles east of the valley of the Judith River.

Above these supposed Eagle sandstones the beds are softer sandstones broken down and mainly covered. They are several hundred feet in thickness and undoubtedly represent the Belly River interval, but the outcrops were too meager to determine much in detail about them.

The dark-colored shales of the Pierre resting on these sandstones form the surface of the bench beginning several miles to the eastward of the coal mine, and the road to Kendall passes over them, several good outcrops showing, especially to the north of the road, but they do not show on the Judith south of the mouth of Warm Spring Creek. However, the Pierre shales appear in the

[1] "Geology of Lewistown Coal Field," *Bull. U.S. Geol. Surv. No. 390*, map.

valley long before Fullerton is reached and at the latter place form the bluffs on both sides of Judith River in typical exposures containing characteristic fossils. The entire thickness does not show at Fullerton but there is here an exposure of at least 400 feet. The total thickness is probably from 600 to 900 feet. Immediately below the Judith River beds which form the summit of the bluffs and the surface of the bench reaching to the eastward, there are from 50 to 100 feet of sandstone with *Halymenites major* and the following invertebrate fossils: *Avicula nebrascana* E. & S., *Tancredia americana* M. & H., *Lunatia subcrassa* M. & H., *Tellina equilateralis* M. & H., and *Mactra* sp. These are identified by Dr. Stanton and referred by him to the Claggett, but it seems to me they are undoubtedly of Fox Hills age, the beds containing them resting on Pierre shales and being immediately followed above by the Judith River beds. The basal layers of the latter series contain *Ostrea subtrigonalis* and other brackish-water forms. The contact between the two formations as seen from the west side of the valley is somewhat irregular, suggesting the unconformity which elsewhere marks the upper limit of the Fox Hills and the base of the Lance formation. Up to this point no faults occur nor is there any evidence of folding nor of overturn. The section is normal and complete, unless a stratigraphic break exists corresponding to the paleontological hiatus at the top of the Fox Hills, the sequence from the Kootenai up through the Colorado and Montana into the Judith River formation being perfect except for the paleontologic and possibly stratigraphic hiatus at the base of the latter.

A short distance below Fullerton the first of three well-marked faults that occur south of Judith Landing crosses Judith River. The direction of this fault is nearly east and west and the dip of the beds thrown down is quite steep (about 20°) toward the northwest. This outcrop, mainly of Fox Hills sandstone and a smaller part of Judith River beds, is underlain by Pierre shales; and above the faulted beds are Pierre shales capped by Fox Hills sandstones (containing invertebrates and *Halymenites major*) which underlie the undisturbed Judith River beds which have a very slight inclination to the north or northwest. The lower slopes of the hill back to the faulted beds is composed of Pierre shales capped with Fox

Hills sandstones and overlying Judith River beds. This fault-line was afterward crossed twelve miles to the eastward near the crossing of Dog Creek. The second fault-line parallel to this one is exactly like the first, but the third one, a few miles south of Judith Landing, is a block fault of Fox Hills sandstones with a steep dip on the southwest side. From Judith Landing a trip up Dog Creek for about three miles above its mouth was taken to the point visited by Stanton and Hatcher and here another fault similar to those just referred to was seen showing, not only on Dog Creek, but extending across to the north side of the Missouri River. Lack of time prevented a tracing of these lines, and also precluded the close examination of the complicated conditions shown on Dog Creek.

That the structure is complicated is shown by the following conditions. In Plate 2, opposite p. 36, of *Bulletin No. 257* of the Geological Survey is shown a cliff of sandstone referred by Dr. Stanton to the Upper Eagle, which was found by him to be very fossiliferous, containing the following forms: *Cardium speciosum*, *Tellina montanensis*, *Baroda* sp., *Callista* sp. Cf. *C. deweyi*, *Mactra alta*, *Mactra formosa*, *Lunatia subcrassa*. This cliff was visited by us in July, 1911, and in horizontal beds lying below this cliff the following vertebrate remains were collected: *Champsosaurus* vertebrae, carnivorous dinosaur tooth, *Paleoscincus* tooth, Crocodile teeth, *Brachychampsa* (?) tooth, ganoid fish remains, and shark's teeth. These were identified by Mr. C. W. Gilmore of the U.S. National Museum, who says: "All of these forms may be found either in Judith River or the Lance formation with the possible exception of *Brachychampsa*, which at this time has been recognized only at Hell Creek and in the Ceratops beds of Wyoming." In the same series of beds 400 feet *higher* the following were found: carnivorous dinosaur tooth, a small ceratopsian tooth, *Trachodon* tooth, a turtle (not determinable), a crocodile (probably *Leidyosuchus*) and remains of a ganoid fish and shark's teeth. Below the lower of these two fossiliferous beds (both of which are regarded as of Judith River age) in beds standing almost on end the following invertebrates were obtained, viz., *Avicula nebrascana* E.&S., *Tancredia americana* M.&H., *Tellina equilateralis* M.&H., *Mactra* sp., *Lunatia subcrassa* M.&H., *Cardium speciosum* M.&H.,

Mactra formosa M. & H. These have been identified by Dr. Stanton, who says: "This lot is apparently made up of collections from two distinct horizons. The first five species of the list are from the upper half of the Claggett, the other two probably from a lower bed which may also be in the Claggett or possibly as low as the Eagle."

There is no mixing of horizons *stratigraphically*, as all of these specimens collected by the writer came from an area that can be included within one's outstretched arms, in which the exposure is perfectly shown; therefore they are *all* from the Claggett of Dr. Stanton, or, according to the writer, from the Fox Hills formation, as the species are found in the Fox Hills of Colorado and other portions of the Rocky Mountains. The fact that two of the species are mentioned as "possibly" of Eagle age and these two rather widely distributed in the Fox Hills raises the question as to whether the sandstones occurring so frequently along the Missouri River and supposed to be brought to the surface by faulting may not be of Fox Hills age rather than of Eagle age, especially as lithologically they are almost indistinguishable. It was impossible, as already intimated, to unravel the structure here in the few hours we spent at this locality.

Returning to Fullerton we crossed the county to the eastward, the surface formation until we reached Dog Creek being the beds of the Judith River formation. East of Dog Creek the faulting was again in evidence, beds of Pierre and Judith River age mainly being involved, although it may be found later that the Eagle sandstones and Belly River formation are present in some of the ridges. So much of the surface of this area is covered and the lines of the faulting so numerous (there being at least six of them separated by areas of Pierre shales) that no attempt was made to unravel the complicated structure. Until a complete areal survey is made, the structure here must remain obscure. At Mauland (now known as Boe's ranch), which is about 10 miles south of the Missouri and about 20 miles east of Dog Creek, well-marked exposures of Judith River, as determined by fragments of vertebrate remains, were seen at the ranch dipping steeply (20° to 25°) against a fault-line, separating them from the Pierre shales, which are

almost horizontal in this immediate place but only a short distance away are seen to dip gently toward the north or northwest beneath the supposed Judith River beds which cap the ridge. The relations of the Pierre and overlying Fox Hills in the latter outcrop were plainly seen, as they dip normally beneath the Judith River beds.

From this point we turned back toward Dog Creek, crossing it about eight or ten miles farther south than our crossing on the way eastward, and thence we returned to Lewistown. The principal result of this trip was the determination of the geological position of the true Judith River beds to be above the Fox Hills, verifying Stanton's observations of 1894, and confirming his original opinion that when the Fort Pierre shales—or, as he renamed them, Bearpaw shales—appear to lie above the *Judith River beds* it is due to faulting.

It was determined to examine next the supposed Judith River exposures in other areas mentioned by Stanton and Hatcher. Here again we went to the southward to avoid the complicated region about Bearpaw Mountains, especially as lack of time prevented our going northward to and beyond the Canadian line. The areas in Assiniboia are, according to the Canadian reports, of undoubted Belly River age, as described first by Dr. G. M. Dawson.[1] These beds were traced by Stanton and Hatcher to the vicinity of Havre, Mont., where they lie beneath Pierre shales without any unconformity or faulting. The first area visited by us was that on Fish Creek in which the section was gone over from the Jurassic up through the Cretaceous to the Fort Union. This section is essentially the same as that given by Douglas[2] and subsequently examined by Fisher. However, instead of finding Laramie resting on the Fox Hills, in which the characteristic *Halymenites* occurs, the beds lying immediately above were found to be of Livingston age with a typical flora, and between them and the undisputed Fort Union are good exposures of the Lance formation. It is, however, in the lower portion of the section that we are most interested. It is possible, as Fisher suggests, that the beds referred by Douglas to the Jurassic may belong to the Kootenai, as there is

[1] *Geol. Surv. Canada, 1882–84*, p. 116*c*.

[2] *Proc. Am. Phil. Soc.*, XLI, 207–24.

a lithological resemblance, but no fossils were found to prove this[1] supposition.

In these supposed Jurassic beds Douglas secured bones of a large dinosaur, above which he recognized several hundred feet of sandstones and shales, extending to the Benton, the upper part of which he says probably belongs to the Dakota formation. In the dark shales and sandstones which he refers to the Benton he obtained shells, all of Benton types. The Benton is succeeded above by grey sandstones and shales with some bands of limestone. He estimates these beds to have a thickness of 700 to 800 feet and refers them to the Niobrara, speaking also of the coal occurring above the middle. This coal and the beds below are probably to be correlated with the Eagle formation. In the upper part of the series not far below the top, I obtained a *Sequoia Reichenbachi*, probably the same species of Sequoia noted by Douglas as occurring near the same horizon in these beds. The beds so far as observed are nearly vertical in position, forming hog-back ridges, and the change to the badland beds, which are stratigraphically higher and nearly horizontal in position, occurs within a very short distance, though there is little doubt as to the two being conformable. These fresh-water beds are those which he calls the Fish Creek beds and he correctly correlates them with the Belly River beds of Canada with which their stratigraphic position agrees perfectly. They are overlain, as are the Canadian Belly River beds, by a great thickness of Fort Pierre shales. These exposures, first discovered by Douglas, are referred to by Stanton as follows:

> Not being familiar with the Judith River beds, Mr. Douglas was unable to recognize the identity of the Fish Creek and Judith River outcrops. In their stratigraphic position, as well as in their lithologic and faunal characters, they are almost identical with the Judith River beds farther north and should be referred to that formation.[2]

As noted above, the stratigraphic position of these beds is the same as that of the Belly River beds in Canada and not that of the Judith River beds of Montana. There is of course a general resemblance lithologically in them to the Judith River beds and

[1] *Economic Geology*, III (1908), 83, 84.

[2] *Bull. U.S. Geol. Surv. No. 257*, 1905, p. 59.

also to those of the Lance formation. It was this resemblance, as we have seen, that in Canada caused the confusion between the Belly River beds and the Edmonton beds in the minds of Dawson and other Canadian geologists. McConnell,[1] referring to some of the fresh-water and brackish-water shells that are common to the two, says:

> Their reappearance in the latter [Edmonton or Laramie] after a prolonged absence, during which the Pierre and Fox Hills—both marine formations—were deposited, affords an example of the extinction of a fauna over wide areas, its at least partial survival in sheltered localities, and the subsequent redistribution of some of its members over the same area on the recurrence of favorable conditions. . . . . Vertebrate remains occur in part of this formation, and are strewn in large quantities over the faces of some of the sections. They are, however, nearly always in a poor state of preservation, and crumble to pieces when disturbed.

This faunal resemblance is noted by all the Canadian geologists. Whiteaves,[2] referring to it, says that from purely invertebrate paleontological evidence the Belly River, Laramie [Lance] and Judith River beds cannot be separated from each other. As to the vertebrate fauna, Professor H. F. Osborn, who has made a comparison of the land and fresh-water forms from these various horizons, says that there is very little in common between the Belly River fauna and that of the Laramie [Lance] of Wyoming and Colorado so far as described, and that most of the dinosaurs will probably be found to be separated generically.[3] His table[4] shows that of the 35 species accredited to the Belly River series only 9 are common to the Judith River. As to the resemblance between the Judith River beds and the Lance formation more will be said later on. There are no Ceratopsidae in common and this we find to be the case with the Belly River series in the Fish Creek section and in the Willow Creek section which was the one next examined by us.

On Willow Creek the section begins with outcrops of Benton shales. Above these shales is a series of sandstones and shales

[1] *Geol. Surv. Canada*, Vol. I, 1885, Montreal (1886), p. 65*c*.

[2] *Contributions to Canadian Paleontology, U.S. Geol. Surv.*, I, 55.

[3] *Contributions to Canadian Paleontology*, III, Pt. 2 (1902), p. 10.

[4] *Ibid.*, pp. 11 f.

exactly like those near Crawford's ranch on Fish Creek, which, there the same as here, dip beneath badlands exposures of Belly River beds, having a total thickness of about 180 feet. The Belly River beds, here, closely resemble those seen in the Fish Creek section and, like them, pass conformably beneath the soft dark shales of the Pierre, all dipping gently toward the southeast. The Belly River beds contain fossil wood in abundance near the base of the outcrops, and a few feet higher in the section the plants were collected which were described by Dr. Knowlton[1] and said to exhibit an undoubted relationship with the flora of the Dakota group and very little affinity with that of the Laramie or Fort Union as they would if from the true Judith River beds. There can be no doubt as to the Belly River age of these beds. They contain the usual fresh-water shells and the overlying beds contain a characteristic Pierre fauna referred by Dr. Stanton to the Bearpaw. The beds between the top of these Fort Pierre shales and the Fort Union horizon, from which a typical Fort Union flora was obtained and which Dr. Stanton says[2] "should, from their stratigraphic position, contain the equivalent of the Fox Hills and the Laramie as well as the Livingston formation," are of Lower Fort Union age—that is, are referable to the Lance formation. These (Lance) beds rest immediately upon the Pierre without any Fox Hills or Livingston beds between them, and as for the Laramie, no beds referable to this formation have yet been found in this region. A careful search was made for Fox Hills fossils, but not a trace could be found of them nor of anything referable to the Livingston, so, as at Forsyth, which was the last place visited by us, the Lance formation is in immediate superposition on the shales of the Fort Pierre.

[1] *Bull. U.S. Geol. Surv. No. 257*, 1905, pp. 129–55.

[2] *Ibid.*, p. 58.

MODIFICATIONS OF THE *QUANTITATIVE SYSTEM OF CLASSIFICATION OF IGNEOUS ROCKS*

WHITMAN CROSS, J. P. IDDINGS, L. V. PIRSSON, H. S. WASHINGTON

During the nine years that have elapsed since the publication of the *Quantitative System of Classification of Igneous Rocks* it has been used with increasing frequency by petrographers in all parts of the world. Naturally, it has been chiefly employed in conjunction with the qualitative system as a means of more exact definition, and as an aid in the correlation and comparison of rocks from different regions. Besides the commoner rocks that belong to the systematic divisions for which magmatic names were originally suggested, numerous varieties have been described that belong to divisions not named by the authors of the system, and some that were not known to exist at the time of its publication. For these divisions magmatic names have been suggested by petrographers from time to time, and the following have come to our attention since the first appearance of the system in 1902:

I. 2.2.3. Cardiffose (F. D. Adams and A. E. Barlow, 1910).
I. 3.1.4. Taurose (H. S. Washington, 1904).
I. 5.3. Piedmontase; I. 5.3.4. Piedmontose (T. L. Watson and S. Taber, 1912).
I. 5.3.2. Mazarunose (H. S. Washington, 1903).
I. 5.5.4–5. Caledonose (Lacroix, 1911).
I. 6.2.3. Procenose (H. S. Washington, 1906).
I. 6.2.5. Raglanose (F. D. Adams and A. E. Barlow, 1908).
I. 7.1.2. Craigmontose (F. D. Adams and A. E. Barlow, 1908).
I. 7.1.3. Appianose (H. S. Washington, 1906).
I. 8.2. Monmouthase; I. 8.2.4. Monmouthose (Adams and Barlow, 1908).
I.II. 1.5. Indare; I.II. 1.5.1. Uralase; I.II. 1.5.1.3. Uralose (H. S. Washington, 1903).
I.II. 1.5.3. Dungannonase; I.II. 1.5.3.4. Dungannonose (Adams and Barlow, 1908).
I.II. 1.5.4. Borsowase; I.II. 1.5.4.3. Borsowose (H. S. Washington, 1903).

I.II. 1.5.5. Kyschtymase (H. S. Washington, 1903).
II. 5.1.5. Kirunose (Geijer, 1910).
II. 5.3.2. Auruncose (H. S. Washington, 1906), Lincolnose (Ida Ogilvie, 1907).
II. 6.2.2. Vicose (H. S. Washington, 1906).
II. 7.1. Lujavrase (C.I.P.W., 1902). Chibinase, II. 7.1.4. Lujavrose (C.I.P.W., 1902). Chibinose (V. Hackman, 1905).
II. 7.2.2. Braccianose (H. S. Washington, 1903).
III. 4.4.4–5. Koghose (Lacroix, 1911).
III. 5.5.4–5. Ouenose (Lacroix, 1911).
III. 6.1.3. Montanose (L. V. Pirsson, 1905).
III. 6.3.2. Ottajanose (A. Lacroix, 1907).
III. 6.4.3. Papenoose (A. Lacroix, 1910).
III. 7.2.2. Jugose (H. S. Washington, 1906).
III. 7.2.3. Cascadose (L. V. Pirsson, 1905).
III. 7.3.2. Fiasconose (H. S. Washington, 1906).
III. 8.1.5. Tavose (V. Hackman, 1905).
IV. 1.$_2$. Quebeciare; IV. 1.$_2$.2. Brunase (J. A. Dresser, 1909).
IV. 1.$_2$. Hawaiiare; IV. 1.$_2$.1. Hilase; IV. 1.$_2$.1.2. Hilose (Daly, 1911).
IV. 1.$_2$.2.2. Palisadose (J. V. Lewis, 1907); Hudsonose (G. S. Rogers, 1911); Thiose (Lacroix, 1911).
IV. 2.$_1$.2. Yamaskase; IV. 2.$_1$.2.2. Yamaskose (G. A. Young, 1904).
IV. 2.$_3$.3.2. Naketose (Lacroix, 1911).
IV. 3.$_1$.2.3. Tuxenose (E. Gourdon, 1908).
IV.II.3.$_1$.2.3. Roselandose (Watson and Taber, 1912).
V. 1.$_3$.2.2. Koswose (J. P. Iddings, 1903).
V. 1.$_4$. Gorduniare; V. 1.$_4$.1. Gordunase; V. 1.$_4$.1.1. Gordunose (U. Grubenmann, 1908).
V. 1.$_4$.1.2. Kakoulimose (A. Lacroix, 1911).
V. 1.$_5$.1.2. Guineose (A. Lacroix, 1911).
V. 2.$_5$.1.2. Permose (J. P. Iddings, 1903).
V. 3. Rhodare; V. 3.$_5$.1. Rhodase; V. 3.$_5$.1.2. Rhodose (C. H. Warren, 1908).
V.II. 2. Mainare; V.II.2.$_3$. Mainiase; V.II.2.$_3$.1.2. Lermondose (E. S. Bastin, 1908).
V.II. 5. Virginare; V.II.5.$_5$. Virginore. (T. L. Watson and S. Taber).
V.II. 5.$_5$.3. Nelsonase; V.II. 5.$_5$.3.5. Nelsonose (T. L. Watson and S. Taber, 1912).
V.II. 5.$_5$.4. Virginase; V.II. 5.$_5$.4.5. Virginose (Watson and Taber, 1912).

There are a few synonyms in this list and in such cases we believe that the law of priority should be applied. Some names

are unnecessary, such as those for presodic subrangs of percalcic rangs, viz: Caledonose and Ouenose.

Recently O. C. Farrington has applied the quantitative system to the classification of stony meteorites, and has suggested 41 new names in conformity with this system, most of them in Classes IV and V, and in subclasses characterized by prominent amounts of metallic minerals. In several cases in which meteorites belong to magmatic divisions already named for rock magmas Professor Farrington has given new names for meteoric magmas in order to distinguish the two groups of bodies.[1]

MODIFICATION OF THE FORMATION OF RANGS AND SUBRANGS IN CLASSES IV AND V

Owing to the fact that the alkali-bearing femic molecules, $NaFe(SiO_3)_2$, Na_2SiO_3, and K_2SiO_3, are not present in rocks of Classes IV and V in sufficient amounts to necessitate the recognition of the femic alkalies in establishing rangs in these classes, although it is conceivable that rocks composed almost wholly of acmite may occur, it is advisable to shift the position of femic alkalies, $Na_2O''K_2O''$, in the arrangement of the base-forming components for the formation of rangs and subrangs. Comparison between them should be made as follows:

Rangs, according to the ratio $\dfrac{MgO+FeO+(Na_2O''+K_2O'')}{CaO''}$

Subrangs according to $\dfrac{MgO}{FeO+(Na_2O''+K_2O'')}$

Sections of subrangs, when needed, according to $\dfrac{FeO}{Na_2O''+K_2O''}$

Subsections of subrangs, when needed, according to $\dfrac{Na_2O''}{K_2O''}$

For all rocks so far known, sections and subsections of subrangs in these classes are not needed and may be neglected. When noticeably alkalic prefemic rocks are found, their place in the system is provided for. By this change the symbols for magma divisions in Classes IV and V are simplified in all cases so far known, by the

[1] Farrington, O. C., Field Museum of Natural History, Chicago, *Pub. 151*, Geol. Ser., Vol. III, No. 9, 1911.

omission of sections of rangs. Those divisions previously called sections of rangs will become rangs with the appropriate change in the suffix. That is, the name hitherto used for the section of rang is to be retained as the name of the rang of the corresponding number, 1, 2, 3, etc., and *i* dropped from the suffix. Thus in Class IV, Order 2, Section 2 (paoliare), Rang 1 will be valbonase, and Rang 3, paolase. In Section 3, texiare, of the same order, Rang 1 will be marquettase; Rang 2 uvaldase. The name texase will be dropped unless subsequently applied to either Rang 3, 4, or 5 of this Section 3. The subrangs remain as first described and named.

Since in Classes II and III subgrads are formed on a basis of the chemical characters of the femic minerals, the process of determining them is to be modified in accordance with the method just described for determining rangs in Classes IV and V. That is, subgrads are to be determined by the ratio $\frac{MgO+FeO+(Na_2O''+K_2O'')}{CaO''}$; sections of subgrads, by the ratio of $\frac{MgO}{FeO+(Na_2O''+K_2O'')}$; and in the exceptional cases in which there is a notable amount of femic alkalies, subsections of subgrads are to be determined by the ratio $\frac{FeO}{Na_2O''+K_2O''}$.

Notation of divisions and symbols.—In order to avoid confusion in the symbols for various divisions in the system, it has been found advisable to number threefold divisions, when used, in conformity with fivefold ones; thus, 1–2, 3, 4–5; since the first division comprises 1 and 2 of the fivefold; the second division corresponds exactly to 3 of the fivefold divisions; and the third division comprises 4 and 5 of the fivefold divisions. This method has already been employed in a number of publications[1] since the first appearance of the system in 1902. It is also advisable to print the numbers of subclasses, suborders, and sections so as to distinguish them from the numbers of regular divisions by placing them below the line rather than above it, thus:

[1] H. S. Washington, "The Superior Analyses," etc., U.S. Geological Survey, *Prof. Paper 28*, 1904; J. P. Iddings, *Igneous Rocks*, Vol. I, 1909, and others.

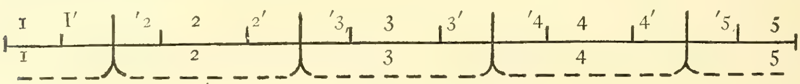
I.$_{\mathrm{II}}$. 5.2.3.=Class I, Subclass II, Order 5, Rang 2, Subrang 3.
IV.$_{\mathrm{II}}$. 2.$_3$.2.2.=Class IV, Subclass II, Order 2, Section 3, Rang 2, Subrang 2.
IV. 4.$_2$.1.4.=Class IV, Order 4, Suborder 2, Rang 1, Subrang 4.

It is to be observed, however, that the number for subrang is placed on the line with rang. This arrangement makes it possible to express the intermediate magmatic divisions by means of marks above the line in the manner explained in the next paragraph.

Intermediate divisions.—In a continuous series of varieties of rock magmas those near one another on opposite sides of any division line are more alike than varieties at the extremities of any one division. And so it happens that some rocks differing but little in composition may be given different names, because they belong on two sides of a division line, while other rocks not so much alike are called by the same name and belong to the extremes of the same magmatic division. This condition is inherent in any rigid system of divisions of continuous series. It has not been felt to the same extent in the qualitative system because each petrographer adjusts the elastic definitions of that system to suit his own requirements, and to the confusion of everyone else.

In order to distinguish the extremes of the magmatic divisions already established in the first publication of the *Quantitative System*, and meet the needs of closer classification, or correlation, it is desirable to establish *intermediate divisions* throughout the system by placing the boundaries of these divisions half-way between the extremities of the divisions and the centers of the divisions from which the intermediate divisions are to be taken, in conformity with the methods pursued in establishing the first division in the *Quantitative System*. The boundary between adjacent divisions becomes in this way a new centerpoint for each pair of intermediate divisions.

In the notation of intermediate divisions the halves of each pair of divisions falling within the adjacent large divisions are designated as parts of the large divisions, and are not given new and independent designations. Thus the intermediate divisions in any fivefold series are as follows:



In order to simplify the expression of these divisions they are printed with prime marks as follows: 1, 1′, ′2, 2, 2′, ′3, 3, 3′, etc. A rock may belong to I, 2′, ′4, 3, or I′, 2, ′2, 3′. For convenience in determining the position of any magma with respect to these divisions a scale of ratios is given in Fig. 1. Magmas belonging to intermediate divisions may be described in terms of the variations indicated by the symbols; as, for example, I′, 3, 2′, 3 (tehamose) is a femic, calcic tehamose; more precisely, a more femic, more calcic tehamose than the central varieties, since these also contain femic and calcic components.

Transitional magma names.—It was pointed out in the first publication of the *Quantitative System*, p. 166, that a rock whose magma belongs so near a boundary line between named divisions that it should be considered a transitional variety should receive a compound magma name, made by uniting the names of the two divisions concerned and connecting them with a hyphen. The name of the division within which the magma belongs is placed last. This has been done in numerous instances, but no definite statement has been made as to the limits of the magmas that may be called transitional. It is here proposed to fix the limits half-way between the boundary between named or numbered divisions, and the boundaries of the intermediate divisions described in the preceding paragraphs. This conforms to the general principles of divisions in the *Quantitative System* and establishes a still smaller division of the petrographic series. It does not appear desirable to extend the use of compounded names to the whole range of intermediate magmas, which are sufficiently designated by symbol.

In case a rock is transitional in more than one respect, as in subrang and in rang, or in rang and order, or in class, order, and rang, or in all possible respects, it is necessary for convenience to select two magmatic names to form the compound name, and express the remaining transitions by descriptive terms or symbols. Since the magmatic name commonly employed in designating a rock is that of its subrang, the name to be compounded with it should be that of the subrang toward which it is transitional through the nearest classificatory division in which it is transitional. Thus, in the case of a rock whose symbol is II.(3)4.3(4).4; that is, one

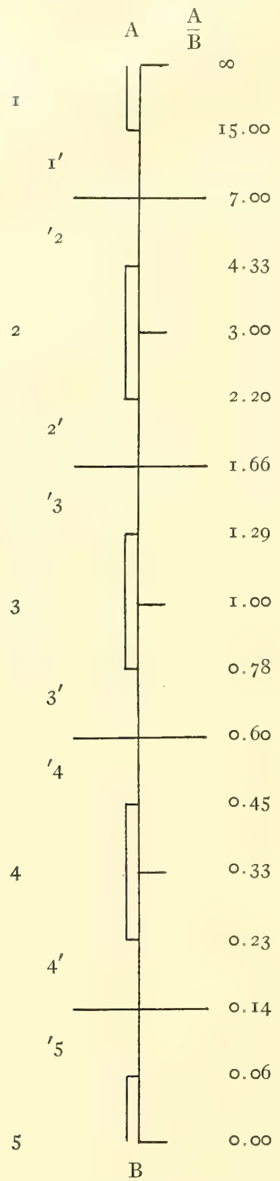


FIG. 1.—Limiting Ratios for Intermediate Magmas.

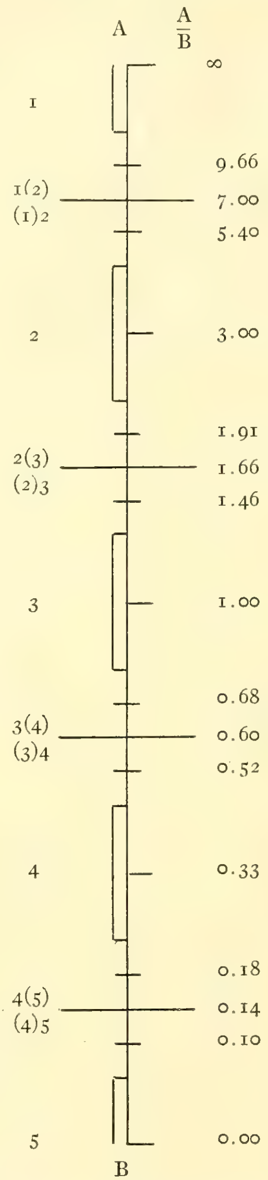


FIG. 2.—Limiting Ratios for Transitional Magmas.

which is in Order 4, near 3, and in Rang 3, near 4; the name for the subrang is tonalose, but as it is near Rang 4 it should be called bandose-tonalose; and the transition toward Order 3 should be expressed by describing it as extremely quaric bandose-tonalose. If it were transitional toward Class I, it would be extremely salic; if toward Class III, extremely femic—the term *extremely* signifying that it is *near the limit* of the division with respect to the factor named, the actual amount being small in some cases. A scale of ratios to be used in determining the limits of transitional divisions is shown in Fig. 2.

In order to express in the symbol that a rock has a *transitional* position in the quantitative classification, the number of the division toward which it is transitional is to be placed in curves, thus I.4(5).2.(3)3, or II.5.'3.4(5).

Experience has already shown that it is eminently undesirable to base subrang or other names on occurrences of *transitional* rocks.

Changes in the norm.—It has been found advisable to omit the calculation of normative sodalite and noselite on a basis of the Cl and SO_3 in rock analyses, because these substances are such small components of sodalite and noselite molecules that any error in the assignment of Cl or SO_3 to these molecules may make a large error in the amount or normative noselite and sodalite. Moreover, there are difficulties in the analytical determination of Cl and SO_3 on the one hand, and they may occur in quite different mineral compounds on the other. The method of calculating the norm has been modified, therefore, by allotting to Cl and SO_3 sufficient Na_2O to form NaCl and Na_2SO_4, and including these compounds among the salic components. This modification has been incorporated in the statement of the *Quantitative System* in Vol. I of *Igneous Rocks* by one of the authors.

The rule with regard to the allotment of CaO and TiO_2 to form titanite or perovskite is to be modified to suit those cases in which there is no excess of CaO after calculating anorthite; that is, when there is no femic CaO. In the ordinary case in which titanite, or perovskite, is formed there is femic CaO available, but there are magmas, not commonly met with, in which anorthite is associated with abundant rutile, as in certain rutile-bearing pegmatites.

From these it is seen that aluminum and calcium combine to form the orthosilicate, anorthite, in the presence of uncombined TiO_2, so that the rule regarding the calculation of titanite and perovskite, rule 3(*b*), should be modified to read: Excess of TiO_2 over available FeO is combined with CaO in the ratio of $CaO : TiO_2 :: 1 : 1$ for titanite and perovskite, *after the allotment of CaO to* Al_2O_3 *for anorthite*, rule 5(*a*), and according to the silica available, etc.

Recent investigations in the Geophysical Laboratory of the Carnegie Institution in Washington have shown that the akermanite compound is $3CaO . 2SiO_2$, not $4CaO . 3SiO_2$ as formerly stated. This involves changes in the formulae for the calculation of normative akermanite as follows:

For the reduction of diopside to akermanite

$$Y = \tfrac{2}{5} \text{ of the deficit of } SiO_2$$
$$Y = \text{molecules of akermanite } (3CaO . 2SiO_2).$$

For the reduction of wollastonite to akermanite

$$Y = \text{deficit of } SiO_2$$
$$Y = \text{molecules of akermanite } (3CaO . 2SiO_2)$$

If there is not sufficient wollastonite to satisfy the deficit of silica, recalculate the molecules of diopside and wollastonite so as to make akermanite, olivine, and diopside by means of the formulae

$$2x + 2y + \frac{z}{2} = \text{available } SiO_2$$
$$x + 3y = \text{molecules of CaO}$$
$$x + z = \text{molecules of MgO+FeO}$$

Where x=molecules of new diopside, y=molecules of akermanite, and z=molecules of olivine.

Common errors in the calculation of norms.—Although clearly explained in the statements published regarding the method of calculating normative minerals in the *Quantitative System* and the method of determining rangs and subrangs, there often appears to be a misunderstanding in the minds of some petrographers as to the CaO and K_2O and Na_2O, which are to be used in determining the rang of a rock in Classes I, II, and III. It is a common error to use all the CaO and K_2O+Na_2O in the rock analysis in the ratio

$\frac{CaO'}{K_2O'+Na_2O'}$, instead of only the salic CaO and salic K_2O and Na_2O; that is, only the CaO allotted to normative anorthite, and only the K_2O and Na_2O allotted to normative orthoclase, albite, leucite, nephelite, and NaCl or Na_2SO_4. In like manner the CaO, Na_2O, and K_2O used in determining rangs, subrangs, and sections of subrangs in Classes IV and V by the ratios $\frac{MgO+FeO+Na_2O''+K_2O''}{CaO''}$, etc., are only the femic CaO and femic Na_2O and K_2O; that is, the CaO that has not been allotted to anorthite, and the Na_2O and K_2O not allotted to salic minerals.

An error is sometimes made in calculating the rangs and subrangs in classes IV and V. The MgO and FeO involved are all the MgO and FeO in all the femic minerals, silicates and non-silicates; that is, all in the rock analysis.

Misuse of the terms salic and femic.—There appears to be an indifference among petrographers as to the correct use of scientific terms, which is perhaps inherent in the conditions attending the beginnings of any new branch of science, and suggests that indifference to the manners and customs of old established communities which is characteristic of frontier life in newly settled countries. It indicates a sense of self-sufficiency on the part of the individual petrographer which, in the matter of his use of words, is typified in the conscious superiority of "Alice's" friend "Humpty Dumpty" over these servants of human speech.[1] The petrographer also has no intention of being mastered by mere words, and is in the habit of using them as he himself chooses, without regard to original

[1] "There's glory for you," said Humpty Dumpty.

"I don't know what you mean by glory," Alice said.

Humpty Dumpty smiled contemptuously. "Of course you don't—till I tell you. I meant there's a nice knock-down argument for you!"

"But glory doesn't mean 'a nice knock-down argument,'" Alice objected.

"When *I* use a word," Humpty Dumpty said in rather a scornful tone, "it means just what I choose it to mean—neither more nor less."

"The question is," said Alice, "whether you *can* make a word mean so many different things."

"The question is," said Humpty Dumpty, "which is to be master—that's all."—*Through the Looking Glass*, by Lewis Carroll; Carl Ludwidge Dodgson, Mathematician, Oxford.

definition, or others' usage. Witness the frequent misuse of the chemical terms "acid" and "basic" as applied to the limesoda-feldspar series. Oligoclase is often said to be a more "acid" feldspar than andesine, and labradorite a more "basic" one. It is not to be assumed that petrographers misusing these terms are wholly ignorant of chemistry. We, also, are petrographers and understand how we have done such things. We plead guilty to various degrees of indifference, lack of enterprise, and ignorance.

The petrographical custom of redefining any rock name to suit individual preference and the resulting multiplicity of definitions is, no doubt, in part responsible for this common indifference to all technical terms, whether distinctively petrographic or derived from other sciences. In some cases, names of rocks and technical terms have been so vaguely defined in the first instance that there is latitude of judgment in their application and an invitation to improve their definition. But when the first definition of any term has been precise and clearly specific, its misuse and distortion are inexcusable.

The terms *salic* and *femic* were applied definitely to certain minerals chosen to form norms of igneous rocks in the *Quantitative System of Classification*. They were applied strictly to calculated normative minerals: *salic* to normative quartz, feldspar, lenads, zircon, and corundum; *femic* to normative non-aluminous ferro-magnesian, and calcic pyroxenes, olivines, and other minerals specifically enumerated and described. It excluded aluminous pyroxenes, amphiboles, micas, etc., to which the term *alferric* was applied.

Some petrographers have fancied the terms salic and femic as short words, which they wish to apply to modal quartz, feldspar, and feldspathoid minerals in one case, and to all modal ferro-magnesian minerals in the other. These terms have also been applied to major rock groups. Such applications are not proper uses of these terms, and introduce confusion where it can be easily avoided.

Felsic and mafic.—Short expressions are useful in the general or qualitative description of rocks for the feldspathic minerals and quartz on the one hand, and for the ferromagnesian minerals on the

other. The proper course is to create new terms for new or distinct conceptions, and not use one technical word in two or more quite different ways. To do so is as though some one should call all mammals *marsupials*, because he prefers the word marsupial; or should call all predaceous birds owls, because it is a short, convenient word. Since short, comprehensive terms are needed for modal feldspathic minerals, and for modal ferromagnesian minerals, and for rocks made up predominantly of these groups of minerals, we suggest the term *felsic* for the group of modal feldspars, feldspathoids, and quartz, and the term *mafic* for the group of modal ferromagnesian minerals of all kinds. The term *femag* has been used recently by Johannsen[1] for ferromagnesian minerals, but it appears to us to be objectionable both in form and in sound.

[1] A. Johannsen. *Jour. Geol.*, XIX (1911), 319.

ISOSTASY, A REJOINDER TO THE ARTICLE BY HARMON LEWIS

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In the *Journal of Geology*, Vol. XIX, No. 7, October-November, 1911, pp. 603–26, there was published an article by Mr. Harmon Lewis, entitled "The Theory of Isostasy," which is a direct attack on three publications by John F. Hayford, namely, *The Figure of the Earth and Isostasy from Measurements in the United States*, *Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy*, both published by the Coast and Geodetic Survey, and "The Relations of Isostasy to Geodesy, Geophysics and Geology" published in *Science*, pp. 199–208, February 10, 1911. The attack is direct and positive. Hence this rejoinder is written in a similar manner. The critic may not reasonably object to having his article treated in the manner in which he has treated the publications criticized.

Mr. Lewis claims in his article that Hayford has made a fundamental error in his geodetic investigation, an error in method which vitiates all the conclusions reached. The greater portion of the article is devoted to setting forth this alleged error of method and its consequences. A few pages in the article are devoted to the proposition that since the theory of isostasy does not explain all of the geological facts which have been observed, isostasy probably does not exist.

Hayford believes that Mr. Lewis has in his article, probably unintentionally, overstated even his own extreme views. Hayford is certain that the alleged fundamental error in method in the geodetic investigation, which Lewis sets forth, is not an error and, moreover, that if Lewis had followed his own line of thought to its logical conclusion, he would have convinced himself that no error had been made. The forms of statement used by Mr. Lewis lead one to think that he has some positive basis for other

conclusions from the geodetic evidence than those given by Hayford. A careful reading of the article shows, however, that Lewis has simply suggested that other conclusions are possible. Hayford believes that the arguments in Mr. Lewis' article which are based on geological evidence are essentially weak and in part erroneous.

This rejoinder is an attempt to show briefly some of the basis for the writer's beliefs as expressed in the preceding paragraph. In the first part of this rejoinder practically all of the evidence cited was available to Mr. Lewis before he wrote his paper. In the latter part some new evidence, from gravity observations, is utilized which has not heretofore been accessible to Mr. Lewis but which is now accessible to all interested persons.

Mr. Lewis claims that Hayford made a fundamental error in that "the most probable depth was calculated on the assumption of completeness. If the assumption of completeness was wrong, the depth of compensation which would appear most probable would not be the true depth of compensation but a depth which would counteract the effect of the wrong assumption in regard to the completeness" (p. 612). Referring to the same matter, on p. 625, Mr. Lewis writes, "It is believed that Hayford made an error in determining the degree of completeness of compensation which invalidates his conclusions, for he assumed complete compensation in calculating the depth and then used this depth to calculate the degree of completeness." In contrast to the published conclusions by Hayford,[1] Mr. Lewis writes in connection with the same matter (p. 612), "We are forced to conclude that, from the geodetic evidence alone, neither the depth nor the degree of completeness of isostatic compensation can as yet be considered settled."

Recur for a moment to Mr. Lewis' statement (p. 612), that "If the assumption of completeness was wrong, the depth of compensation which would appear most probable would not be the true depth of compensation but a depth which would counteract the effect of the wrong assumption in regard to completeness." This statement involves in itself an assumption which is absolutely essential to Mr. Lewis' whole argument, namely, that the counter-

[1] See *The Figure of the Earth and Isostasy*, pp. 164–66, 175, and *Supplementary Investigation*, pp. 59, 77.

action suggested by him is possible. Now it happens that such counteraction is nearly impossible to any appreciable extent in the computations actually made. If Mr. Lewis had followed his own course of reasoning farther than he did, using the data printed in the publications criticized he would have convinced himself of this.

He carries his reasoning farther on pp. 616–17 than elsewhere in his article. In the paragraph commencing near the top of p. 616 he shows that if with assumed complete compensation the assumed depth of compensation is made smaller, the reduction factors for each ring become smaller and that, on the other hand, if the isostatic compensation is assumed to be less than complete, the reduction factor for each ring becomes larger. It is also shown that when both these changes in assumption are made at the same time, the reduction factor becomes smaller for certain rings and larger for others. On p. 617 a concrete case of this kind is shown. The table there printed shows clearly that if in the place of assumed complete compensation extending to depth 113.7 km. one assumes a compensation but one-half complete and extending only to the small depth 19.29 km., the reduction factors for rings 29 to 13, corresponding to topography within 56 km. of the station, are all made smaller and those for the remaining more distant rings are all made larger. Thus far Mr. Lewis' reasoning and results are all correct. For convenience, call such reduction factors as those shown in the middle column of the table on p. 617, Lewis factors, and call those such as are shown in the last column, Hayford factors.

At this point Mr. Lewis' logical process begins to go wrong. For at this point the tacit assumption is made, though not stated, that if the Lewis factors are smaller for some rings and larger for others than the Hayford factors the computed topographic deflections with the isostatic compensation considered will be about the same in the two cases. If so (that is, if the computed deflections are easily made about the same), then with effort corresponding to that already made by Hayford, other factors on Lewis' basis, involving other assumptions as to depth and degree of compensation, can be found which will produce computed deflections more nearly in agreement with the observed deflections

than are those computed by Hayford. This is essentially Mr. Lewis' reasoning.

The tacit assumption is, however, not even approximately true, as shown in the following paragraphs, and hence all reasoning based on the assumption leads to erroneous conclusions.

The reduction factor under discussion is the factor by which topographic deflections for a given ring must be multiplied to secure the resultant deflection due to both the topography and the assumed compensating deficiency or excess of mass below the surface of the earth.

On pp. 26–33 of *The Figure of the Earth and Isostasy* five complete examples of the computations of the topographic deflections are printed. Note that this is one of the publications criticized by Mr. Lewis. His tacit assumption has been tested by using these examples, just as he himself should have tested it.

In the following table the details of the test are shown for two stations. The value shown in the table for each ring is the resultant deflection due both to topography and to the assumed isostatic compensation. The values in the first column which is under the heading "Point Arena" correspond, as indicated in the heading, to the assumption that isostatic compensation is but one-half complete and that it extends to the depth 19.29 km. Each value was obtained by multiplying the topographic deflection for the particular ring, as shown in the example on p. 32 of *The Figure of the Earth and Isostasy*, by the Lewis factor shown on p. 617 of his article. The next column shows the deflections for each ring corresponding to the assumption that the isostatic compensation is nine-tenths complete and the depth as before 19.29 km. The Lewis factors necessary for use in computing this column, as well as those mentioned elsewhere in this rejoinder, were computed from the formula given on p. 615 of the Lewis article. The third column shows the deflections corresponding to the assumption that the compensation is complete and the depth 113.7 km.

According to Mr. Lewis' reasoning the total for the first column under Point Arena, $+53''.73$, should differ but little from the total for the third column, $+15''.67$. The actual difference, $38''.06$, is very large. Similarly the corresponding difference for Uncom-

pahgre, namely, between $-3''.93$ and $+5''.55$ is also large, $9''.48$. Evidently the factors given as examples by Mr. Lewis on p. 617 did not produce the results expected by him.

Ring	Longitude Station No. 1 Point Arena, Cal.			Latitude Station No. 54 Uncompahgre, Colo.		
	Lewis $M=.5$ $h_1=19.29$	Lewis $M=.9$ $h_1=19.29$	Hayford $M=1.0$ $h_1=113.7$	Lewis $M=.5$ $h_1=19.29$	Lewis $M=.9$ $h_1=19.29$	Hayford $M=1.0$ $h_1=113.7$
30	$+''.02$	$+''.02$	$+''.02$	—	—	—
29	+ .04	+ .04	+ .04	—	—	—
28	+ .04	+ .04	+ .04	—	—	—
27	+ .05	+ .05	+ .05	—	—	—
26	+ .02	+ .02	+ .02	$+''.27$	$+''.26$	$+''.27$
25	+ .02	+ .02	+ .02	+ .28	+.28	+ .29
24	+ .01	+ .01	+ .01	+ .21	+.21	+ .22
23	+ .10	+ .09	+ .10	+ .14	+.14	+ .15
22	+ .12	+ .12	+ .13	− .07	−.06	− .07
21	+ .15	+ .14	+ .16	+ .03	+.03	+ .03
20	+ .14	+ .13	+ .15	+ .05	+.05	+ .06
19	+ .22	+ .19	+ .25	− .33	−.28	− .36
18	+ .25	+ .20	+ .29	− .36	−.29	− .41
17	+ .28	+ .21	+ .34	+ .22	+.16	+ .26
16	+ .43	+ .27	+ .55	+ .67	+.42	+ .85
15	+ .90	+ .45	+1.17	+ .92	+.46	+1.19
14	+1.34	+ .53	+1.69	+1.05	+.42	+1.33
13	+2.11	+ .66	+2.42	+1.27	+.40	+1.45
12	+2.59	+ .68	+2.46	+ .75	+.20	+ .71
11	+3.01	+ .70	+2.11	+ .07	+.01	+ .04
10	+2.90	+ .63	+1.34	− .50	−.11	− .23
9	+3.01	+ .62	+ .83	− .54	−.11	− .15
8	+4.59	+ .95	+ .71	− .02	.00	.00
7	+4.72	+ .95	+ .38	− .42	−.08	− .03
6	+5.05	+1.02	+ .20	− .30	−.06	− .01
5	+4.66	+ .93	+ .09	− .58	−.12	− .01
4	+5.04	+1.01	+ .05	− .82	−.16	− .01
3	+5.02	+1.00	+ .03	−1.34	−.27	− .01
2	+4.09	+ .82	+ .01	−2.04	−.41	.00
1	+2.81	+ .56	+ .01	−2.54	−.51	− .01
Totals	+53.73	+13.06	+15.67*	−3.93	+.58	+5.55*

*The slight discrepancies, too small to be of any consequence, between these totals and those printed on p. 55 of *The Figure of the Earth and Isostasy* are due to the effects of omitted decimal places.

Possibly it might be said by Mr. Lewis that this failure to secure a close agreement is due to having made so great a reduction in the assumed completeness of compensation as to much more than counteract the reduction in the assumed depth of compensation. Accordingly the middle column has been inserted in the above

table corresponding to the assumption that the compensation is nine-tenths complete and the depth is 19.29 km. This gives a closer agreement in each case, as should be expected, since the assumption is nearer to that made by Hayford, but still the differences from Hayford's values are large—2″.61 for Point Arena and 4″.97 for Uncompahgre.

If Mr. Lewis had followed out his own line of thought, when he reached this point he should have inquired what value of M, expressing in his notation the completeness of compensation, would make his values agree with Hayford's values. If he had done so he would have found that a close agreement would occur for Point Arena with M assumed to be about .87 and thus the truth of his tacit assumption would apparently have been confirmed.

Again, if he had tried Mt. Ouray he would have found that with $M=.2$ and $h_1=19.29$ km. the total computed deflection is $-10''.02$, practically in agreement with the Hayford value. Note the contrast between the reduction to compensation only one-fifth complete necessary at this station to neutralize the effect of the assumed reduction in depth of compensation and the comparatively slight reduction, to .87, necessary at Point Arena.

But if Mr. Lewis had continued still farther and tried the same thing for Uncompahgre he would have found that for $M=1.34$ and $h_1=19.29$ km. the total computed deflection is $+5''.47$, practically in agreement with Hayford's value. The value 1.34 for M indicates 34 per cent of over-compensation. In other words, for Uncompahgre it takes an assumption of one-third over-compensation to neutralize the assumption of a reduction of depth of compensation, whereas Mr. Lewis' whole argument is based upon the assumption that under-compensation is always necessary for such neutralization.

The following table shows the results of the tests made in preparing this rejoinder using the five stations[1] which were available to Mr. Lewis. Each of the Lewis values which lies nearest to the Hayford value for that station is printed in italics. The values

[1] For all the 733 stations involved in the investigation the total topographic deflections are printed, but those for each separate ring are printed for these five stations only. Hence these are the only stations on which it was possible for Mr. Lewis, using publications only, to make the test indicated.

in the table are the computed deflections on the different assumptions indicated. They correspond to the totals at the foot of the preceding table.

	Longitude Sta. No. 1, Point Arena, Cal.	Azimuth Sta. No. 59, Mt. Ouray, Colo.	Latitude Sta. No. 54, Uncompahgre, Colo.	Latitude Sta. No. 164 Calais, Me.	Azimuth Sta. No. 115, Knott Island, Va.
Hayford					
$M=1.0,\ h_1=113.7$	$+15''.67$	$-10''.03$	$+5''.55$	$-0''.51$	$-1''.90$
Lewis					
$M=0.2,\ h_1=19.29$ ...	......	*−10.02*	....	....	....
$M=0.5\ \ h_1=19.29$ ...	+53.73	− 8.22	−3.93	−16.00	−27.19
$M=0.9\ \ h_1=19.29$ ...	*+13.06*	− 5.86	+0.58	*− 2.97*	*− 5.52*
$M=1.34\ h_1=19.29$ ...	......	......	*+5.47*	......	......
$M=1.4\ \ h_1=19.29$ ...	......	......	+6.19	......	......
$M=1.6\ \ h_1=19.29$ ...	......	......	+8.36	......	......

If Mr. Lewis had constructed this table, which would have required less than a day of computation, he would have avoided the gross error into which he has fallen. Instead of believing, as indicated in his article, that a large reduction in assumed completeness of compensation of about the same amount for every station would neutralize the large change of assumed depth from 113.7 to 19.29 km. he would have known that for some stations such a neutralization requires a very large reduction of assumed completeness (to $M=.2$ at Mt. Ouray, for example), for others requires a very small reduction (at Point Arena, Calais, and Knott Island, for example), and for others requires an increase of assumed completeness, that is, over-compensation (at Uncompahgre, for example). He would have noticed that for these five stations the average value of M necessary to secure an agreement with the Hayford values is about .9, not far from unity.

If beginning to be skeptical of his own proposition that a reduction in completeness of compensation at all stations would counteract a reduction in assumed depth of compensation, and beginning to suspect that such a counteraction is impossible in the computations as actually made, he had then proceeded to examine into the matter more carefully he might have noted also the following things:

1. That the factors as printed on p. 617 differ very largely for separate rings from the Hayford factors. The maximum

difference is .499, whereas the factor itself can have a total range of only 1.000.

2. That for other various assumed values of M, with the same value of h_1, his factors always differ largely from Hayford's for some rings. If $M = .9$, for example, the maximum difference occurs on ring 14 and is .496.

3. That to secure a close agreement in the computed deflections from two sets of reduction factors used at various stations there must be a close agreement of the factors for the separate rings, not simply an agreement in the average values of the two sets of factors, since the computed deflections for the various rings at a given station differ greatly.[1] At Point Arena, for example, the topographic deflections for various rings vary from $+0''.01$ for ring 24 to $10''.10$ for ring 6, and at Uncompahgre from $+2''.35$ for ring 13 to $-5''.07$ for ring 1. These topographic deflections for separate rings are the quantities which are multiplied by the reduction factors to obtain the computed deflections. Evidently at Uncompahgre a decrease in the reduction factor in ring 13 will not be partly neutralized in effect by an increase of the factor for ring 1, but instead the two effects will be of the same algebraic sign, since the topographic deflections for these rings happen to be of opposite signs.

4. That the proposed Lewis factors corresponding to incomplete compensation are always greater than the Hayford factors for the extreme outer rings (distant topography), and less than the Hayford factors in the inner rings corresponding to topography at a moderate distance. This gives a clue to the reason for the fact that at some stations it requires a decrease in assumed completeness and at other stations an increase to counteract an assumed decrease in depth of compensation. In this connection it is important to note that the 733 stations used in the computation being criticized are in a great variety of locations with reference to near and distant topography.

5. That following the clue suggested in (4), it becomes evident that there is no fixed relation between the effect upon the compu-

[1] Consult pp. 26–33 of *The Figure of the Earth and Isostasy.*

tations of a reduction in an assumed completeness and a reduction in depth.

6. That in a computation such as that being criticized, based upon 733 stations all utilized fully in a single computation, though an error of moderate size in assumed completeness of compensation will produce residuals at the separate stations, it will have an exceedingly small, probably inappreciable, effect on the computed depth of compensation.

7. That the residuals from the computation actually made, which residuals are printed in detail, show that the assumptions are in very close agreement with the truth, and especially that it is impossible that there is any large error in the assumed completeness of compensation.

8. Finally by following the clues indicated in (4) it would be noted that if it were a fact that the actual depth of compensation is much less than 113.7 km. and the compensation much less than complete the residuals of the accepted final computation would show a certain systematic geographic distribution. For example, all longitude stations and all azimuth stations situated on or very near the Pacific coast, like Point Arena, should have residuals of the same sign as Point Arena. The geographic distribution of residuals which would be so produced does not exist.[1]

In short, if Mr. Lewis had carefully examined the evidence available to him, following logically the lines of thought on which he started, he would have reached the conclusion that an error of moderate size in assumed completeness of compensation would produce no appreciable error in the depth of compensation as actually computed, and that the actual compensation certainly departs but little from completeness.

It should be clear from what is here printed that the alleged error in Hayford's method of computation on which Mr. Lewis' whole criticism rests is fictitious. Even if it is not clear to one who reads this very brief statement, it will certainly become perfectly clear to those who will examine the methods in detail with the numerical values before them.

[1] Consult illustrations 5 and 6 of the *Supplementary Investigation of the Figure of the Earth and Isostasy.*

Mr. Lewis suggests more than once in his article that possibly the existing condition is "an over-compensation at a greater depth for land areas with probably complete compensation for ocean areas" or "under-compensation at a shallower depth for land areas with complete or over-compensation for ocean areas" (p. 626).

If Mr. Lewis or anyone else will carefully test these ideas in the manner indicated on pp. 563–70 of this rejoinder he will certainly reach the conclusion that there is nothing in the suggestion. The writer had made such tests, and others, before Mr. Lewis' article was written.

To test such suggestions by complete computations, such as those set forth in Hayford's publications which are under criticism, would be a waste of time. It is not worth while to spend months in testing a suggestion by a complete computation if, as in this case, a rough test made in one or two days will show the suggestion to be in error.

Turn now to another direct and positive statement made by Mr. Lewis, which is closely allied with the questions discussed above. After stating, correctly, that all Hayford's principal computations were made on the assumption that the isostatic compensation is complete, Mr. Lewis continues thus (pp. 610–11), "This was a purely arbitrary assumption on Hayford's part since he gave no reason whatever for believing at the outset that compensation is complete, and furthermore the fact that he later attempts to find the degree of completeness implies that there is no reason to believe at the outset in complete compensation."

Hayford has indicated in various places in his publications that gravitation tends to produce a readjustment of the material composing the outer portion of the earth toward the condition of approximate equilibrium known as isostasy.[1]

Gravitation acts continuously. It certainly tends to produce complete compensation. Is it purely arbitrary to assume complete compensation as a first approximation? The writer believes it is not.

[1] Consult especially *The Figure of the Earth and Isostasy*, pp. 66–67, 166–68, and the Minneapolis address referred to in the first paragraph of this rejoinder. In this address the possible mechanics of the readjustment is indicated.

Moreover, it requires but little consideration to realize that the known shiftings of load at the surface tends to bring about over-compensation in some localities and under-compensation in others. For example, long continued erosion from a high mountainous region tends to produce over-compensation and deposition by a river of transported material at points above sea-level, as for example, during the raising of the land surface of a delta, tends to produce under-compensation. Various actions below the surface of the earth known to geologists and others tend to produce over-compensation in some locations and under-compensation in others. Gravitation by its continuous action tends, therefore, to cause the condition to approach complete compensation from the side of over-compensation in some localities and from the side of under-compensation in others. Gravitation is resisted by rigidity and it is, therefore, to be expected that it will be but partially successful in the attempt to produce complete compensation. The writer believes, therefore, that it was logical to assume that the compensation is complete rather than that either under-compensation or over-compensation predominates. The assumption was made, not arbitrarily, but logically.

However, it is clear that as long as the material composing the earth has some rigidity, some strength available to resist gravitation, and as long as other forces than gravitation certainly are in operation, complete compensation cannot be continuously produced and maintained by gravitation and one must expect local deviations, now of one sign now of the other, from complete compensation. Hence it was desirable to study the residuals from the computations made on the basis of complete compensation to ascertain if possible how much and in what direction the actual compensation departs from completeness in each locality. This has been done with considerable energy. From the investigations of the deflections the conclusion reached is that there is certainly under-compensation in some localities and over-compensation in others but that on an average the compensation departs less than one-tenth from completeness or perfection.[1] A similar conclusion

[1] *The Figure of the Earth and Isostasy*, pp. 164–66, 175, and *Supplementary Investigation*, p. 59.

is reached from the gravity investigation except that the departure of compensation from completeness is somewhat greater than one-tenth.[1]

Turning now to Mr. Lewis' article the present writer is quite willing to let the reader decide whether or not Mr. Lewis' assumptions (p. 626) of over-compensation for all land areas, or of under-compensation for all land areas and over-compensation for all ocean areas, are arbitrary.

The preceding parts of this rejoinder have dealt with those portions of Mr. Lewis' article, which are a discussion of the geodetic evidence of isostasy. Turn now to the portions of his article in which certain geologic evidence is interpreted as being adverse to the existence of isostasy.

On pp. 621–22 Mr. Lewis sets forth the argument that there is much geological evidence of horizontal movements in the outside portions of the earth especially in the form of folding, that the controlling movements of isostasy are assumed to be vertical and hence cannot account for folding, and that the horizontal movement or undertow concerned in isostatic readjustment must be below the depth of compensation and hence so far below the surface as to be very ineffective in producing folding.

There are two fatal defects in this argument as applied to controverting anything that Hayford believes or has written.

First, Hayford has already indicated clearly his belief that the undertow concerned in isostatic readjustment is above, not below, the depth of compensation. In both the figures published in his Minneapolis address the undertow is clearly indicated as being above the depth of compensation and it is also so indicated in the corresponding text. As Hayford puts the undertow comparatively near the surface where it is conceded that it would be effective in producing folding, the existence of extensive folding is a confirmation not a contradiction of his theory of the manner in which isostatic readjustment takes place. It is certainly not fair to hold Hayford responsible, either directly or by inference, for any theory which someone else may believe which involves an undertow

[1] See p. 111 of *Special Publication No. 10*, of the Coast and Geodetic Survey.

situated entirely below the depth of compensation. Mr. Lewis apparently believes such a theory.

Second, the movements which produce isostatic readjustment are necessarily horizontal not vertical. If two adjacent columns of the same horizontal cross-section extending from the surface to the depth of compensation have different masses the readjustment to perfect compensation must involve a transfer of mass out of one column, or into the other, or from one to the other. In any case the transfer must be a horizontal movement, though it may be incidentally accompanied by a vertical movement. Hayford has already shown in print more than once that he understands that vertical movement alone does not produce isostatic readjustment. Moreover, a careful reading of his Minneapolis address will certainly show that he believes that the total amount of material moved horizontally during isostatic readjustment, and especially the total number of ton-miles of such movement, is vastly in excess of the corresponding quantities concerned in the vertical components of the movement which takes place. Hence the folding and other abundant evidence of past horizontal movements observed by geologists confirm Hayford's hypothesis as to the manner in which isostatic readjustment takes place, instead of conflicting with it as Mr. Lewis' article would lead one to think.

In contrast to the paragraph at the top of p. 623 of Mr. Lewis' article in which he claims that "the theory of isostasy does not explain the apparently heterogeneous relation of uplift and subsidence to erosion and deposition," the writer respectfully requests that certain parts of his Minneapolis address be considered in which it is set forth at some length that the movements concerned in isostatic readjustment at a given time and place are probably a function not simply of the facts at that time and place but also of the past facts there and of the current facts at many other places, some at a considerable distance, perhaps hundreds of miles away. If this be true, one should not expect to find a fixed relation of uplift and subsidence at any given point or time to the erosion or deposition in progress at that point at that time. Why does Mr. Lewis ignore this contrast?

So too, when one reads Mr. Lewis' statement (p. 623) that "in

some cases erosion to a peneplain has been followed by subsidence and in other cases by uplift" and notes that the context seems to imply that this cannot be reconciled with the theory of isostasy, one is puzzled to understand why no reference is made to that part of Hayford's address in which two long paragraphs are devoted to setting forth the errors in this particular line of reasoning.

Thus far in this rejoinder only such evidence has been cited as was available to Mr. Lewis when he wrote his article. In May, 1912, the Coast and Geodetic Survey issued a publication entitled *The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, written by John F. Hayford and William Bowie. This contains further evidence pertinent to the questions under discussion.

In the principal computations set forth in this new publication the effects of isostatic compensation upon the intensity of gravity are computed upon the assumption that the compensation is complete and is uniformly distributed to the depth 113.7 km. The depth was adopted from the first figure of the earth investigation by Hayford and the assumption of complete compensation was retained.

Let the evidence furnished by this new publication on gravity now be considered in connection with Mr. Lewis' article.

In the new gravity publication the computations are made by concentric circular zones as in the computations of topographic deflections, but the zones are not the same. In the new publication in the table on p. 100 the effect upon gravity, at each of 41 stations in the United States, of the assumed compensation for all zones out to zone O, covering all areas within 166.7 km. of the station, is tabulated separately from the effect of the topography itself. This enables one to apply two tests as indicated below.

First, let it be assumed that for these 41 stations the compensation is only nine-tenths complete. Then the computed effect of the compensation as shown in the table should in each case be diminished by one-tenth of itself. This would produce a contrary change of the same magnitude in the anomaly, or residual, shown in the fourth column from the last in this table. An inspection of the values shows that for the 41 stations 19 residuals would be

reduced by such a change, 20 increased and two left as before. The test thus gives a neutral result.

A similar test was made on the assumption that the compensation is only one-half complete, as suggested by Mr. Lewis. Such a change would increase 29 of the 41 residuals. This is a strong indication that incompleteness of compensation does not exist to that extent.

But Mr. Lewis might say in this connection, as he did in connection with the deflections of the vertical, that an error in assuming the compensation to be complete had been offset by an error in making the depth of compensation too great. On p. 105 of the new publication there is a table showing the effect upon the computed correction for compensation of changing the assumed depth of compensation from 113.7 km. to 85.3. The ten stations in this table are also in the table on p. 100. Hence it was possible by a comparison of the two tables to compute the value which must be assigned to Mr. Lewis' quantity M, expressing the completeness of compensation, to make the assumed change in completeness at each station counteract the assumed change in depth. The comparison was made and it was found that the ten necessary values of M vary for these ten stations from .56 to 1.78, with a mean of about unity. This showed, just as it has already been shown earlier in this rejoinder, in connection with deflections of the vertical, that there is no fixed relation between the effects due to changes of assumed depth of compensation and those due to changes of assumed completeness.

Both these tests are incomplete because they utilize only a few of the 89 gravity stations and because they utilize only that portion of the compensation which is within 166.7 km. of the station. But the tests give sufficiently decisive results to show that further investigation along this line is reasonably certain to be fruitless.

The most important confirmation by the gravity publication of conclusions previously drawn from deflections of the vertical, is that shown on pp. 117–21 of the gravity publication. From studies of deflections of the vertical 11 specified areas of excessive density (under-compensation) had been located in the United

States and five specified areas of deficiency (over-compensation). The gravity observations confirm the existence of 10 of these 16 anomalous areas, there being a confirmation in every case in which the gravity stations were so located as to give a thorough test. In no case was there a contradiction between the conclusions from the gravity observations and those from observations of deflections of the vertical. If the apparent residuals in each case were due to errors in assumptions, as contended by Mr. Lewis, this confirmation could not occur. In that case the geographic distribution of the residuals would certainly be different in the two cases for the reasons indicated in the following paragraph.

The intensity of gravity at a given station is a summation of the vertical components of the gravitational forces at that point minus the centrifugal force due to the earth's rotation. The deflection of the vertical at a station dealt with in the publications criticized by Mr. Lewis depend, on the other hand, upon the summation of the horizontal components of the gravitational forces at a given point. The pendulum responds mainly to masses which are above or below it. The plumb bob responds mainly to masses which are to the right or left, before or behind the station. Hence any errors of assumption as to the distribution of the isostatic compensation necessarily produce different effects in connection with gravity computations than those same errors of assumption produce in connection with computations of the deflections of the vertical. Hence a study of the two kinds of computations for the same region furnished a very severe test for errors of assumption. It is especially important to note that if a given error of assumption produces residuals in an investigation of deflections of the vertical having a certain geographic distribution that same error of assumption would produce a different distribution of residuals in an investigation of gravity.

In the new gravity publication the computed corrections for the effects of topography and compensation are published in such detail, for every zone at every station, that Mr. Lewis or anyone else has abundant opportunity to test the effects of making the assumptions different from those upon which the computation

was based. The authors of the gravity publication feel confident that such tests, if thoroughly made, will show that the assumptions in the published computations are very near the truth.

The fact that the gravity observations confirm all the conclusions previously drawn from deflections of the vertical is an exceedingly strong indication that there are no fundamental errors in the method of computation used in either investigation.

Reviews

The Geology of the Glasgow District. By C. T. Clough, L. W. Hinxman, J. S. Grant Wilson, C. B. Crampton, W. B. Wright, E. B. Bailey, E. M. Anderson, R. G. Carruthers, with contributions by G. W. Grabham, J. S. Flett, and a chapter on the paleontology by G. W. Lee. Memoirs Geol. Survey Scotland, 1911. Pp. 270; figs. 33; pl. 1.

Sandstones and basalts are the representatives of the Old Red Sandstone period. Associated with the Lower Carboniferous limestones and sandstones are extrusives of basalt, mugearite, and tuffs and intrusives of basalt, dolerite, trachyte, felsite, trachyandesite, trachydolerite, and basaltic and trachytic tuff in vents. In Upper Carboniferous times sedimentation was predominant, although some basic sills and plugs are possibly of this age. In the Permo-Carboniferous there were intrusions of quartz dolerite sills. During the Tertiary, dikes of olivine dolerite were intruded. The Pleistocene and Recent are represented by glacial deposits, old beaches, river terraces, and flood plains.

Coal is the principal economic material and occurs in both the Upper and Lower Carboniferous. Iron carbonate and fire clays are also exploited. Many analyses of limestone are given.

A. E. F.

The Geology of East Lothian. 2d ed. By C. T. Clough, G. Barrow, C. B. Crampton, H. B. Maufe, E. B. Bailey and E. M. Anderson, with contributions by B. N. Peach and John Horne. Memoirs Geol. Survey Scotland, 1910. Pp. 226; figs. 11; pls. 12.

This educational handbook to the geology of the region discusses the formations and their faunas, and describes the associated igneous rocks. The Silurian period is represented by shales, greywackes, grits, conglomerates, and cherts. Two small granite masses, older than the Old Red Sandstone, intrude these formations. The rocks of the Lower Old Red Sandstone period consist of bosses and laccoliths of granite, porphyry, etc., and dikes of porphyrite, felsite, and lamprophyre. The

upper division of this system is represented by conglomerates, sandstones, and marls. The Early Carboniferous rocks are the Calciferous sandstone series with associated extrusives of basalt, trachydolerite, trachyte, tuffs, and ashy conglomerates and intrusives of essexite, teschenite, and analcite dolerite, monchiquite and analcite basalt. Following the Calciferous is the Carboniferous limestone series, in the middle of which is the Edge coal group, the most important strata from an economic point of view in the district. The Upper Carboniferous is represented by the Millstone grit, which is followed by but a slight representation of the true coal measures. At the close of the Paleozoic, dikes and sills of dolerite were intruded. During the Pleistocene, glaciation affected the entire region.

The petrology of the igneous rocks is thoroughly discussed, and numerous analyses are given. The economics of the area consist largely of non-metallics, of which coal is the principal product.

A. E. F.

Annual Administrative Report of the State Geologist for the Year 1910. By HENRY B. KÜMMEL.

Report on the Approximate Cost of a Canal between Bay Head and the Shrewsbury River. By HENRY B. KÜMMEL.

The Flora of the Raritan Formation. By EDWARD W. BERRY.

A Description of the Fossil Fish Remains of the Cretaceous, Eocene and Miocene Formations of New Jersey. By HENRY W. FOWLER.

The Mineral Industry of New Jersey for 1910. By HENRY B. KÜMMEL and S. PERCY JONES.

Geological Survey of New Jersey, Bulletins 1–5, 1911.

1. This bulletin recounts the operations of the Survey. A list of all publications of the present Survey is appended.

2. The sea-level canal upon which estimates were made is to be sixty feet wide with a minimum depth of six feet. Its length is 21.76 miles, a portion of which is along present waterways, and whatever excavating will have to be done will be in unconsolidated material. The estimated cost for the right of way, excavation, bridges, and disposal of material is between $2,152,404 and $2,784,887.

3. The Raritan formation is the oldest non-marine Cretaceous sediment known along the Atlantic. The paleobotanical evidence

indicates an age older than the Dakota group, and probably equivalent to the Cenomanian of Europe, and the Lower Tuscaloosa of Alabama. Part 2 of the bulletin deals with the systematic paleobotany.

4. This is a descriptive summary of the fish remains known within the limits of the state of New Jersey.

5. New Jersey ranks second in the list of states in the value of products from the clay industry. In this a decided increase is shown over the previous year. The production of iron decreased. Zinc mining had a decrease in the amount of ore hoisted, but an increase in tonnage separated.

A. E. F.

The Maxville Limestone. By William Clifford Morse. Geol. Survey of Ohio, 4th series, Bull. 13. Pp. viii+128; figs. 6; pls. 5.

The Maxville limestone is the top of the Mississippian system in Ohio, and has a thickness of about fifty feet. It is underlain by the highest member of the Waverly, and is overlain unconformably by the Sharon conglomerate, the lowest member of the Pennsylvanian. It outcrops between Zanesville and the Ohio River in two well-defined areas, separated by a region in which it is completely lacking. This bulletin adds twelve species to the Maxville fauna hitherto known. A Ste. Genevieve age is indicated with the probabilities that it corresponds to the Ohara member of that formation. In the Appalachian region the Greenbrier limestone is the equivalent in age. One chapter is devoted to abstracts of the literature on the Maxville, and one chapter to the economic uses to which the limestone can be put. Several analyses are given.

A. E. F.

Wirt, Roane, and Calhoun Counties. By Ray V. Hennen. W.Va. Geol. Survey. Pp. xx+573; figs. 6; pls. 15; maps 3.

This is one of the series of county reports being published by the Survey. It is largely descriptive and covers the history of the area, its physiography, general and detailed geology, geologic structure, oil and gas fields, coal resources, clays, road materials, building-stones, and soils. The detailed geologic contour structure map shows the location of the anticlines where the drilling for oil and gas wells would be most favorable. The soil survey of these counties is the work of W. J. Latimer and F. N. Meeker of the Department of Agriculture. The maps are on a scale of about an inch to the mile, and are in a cover separate from the text.

A. E. F.

Observation on the Magdalen Islands. By JOHN M. CLARKE. N.Y. State Mus. Bull. 149, 1911. Pp. 53; pls. 17, and many unnumbered figures.

This picturesque chain of islands in the Gulf of St. Lawrence, with their romantic history of destruction to navigation crafts beginning back in the fifteenth century, and their vicissitudes of land tenure that have demoralized their development, have a simple geology. Below the sedimentaries are badly broken volcanics, associated, in part, with extensive bodies of gypseous clay. The formation of the gypsum is inferred to be due to the action of sulphur on overlying limestones. These limestones and associated shales carry a marine fauna of Mississippian age. Overlying these is a series of red sandstone of Permian age. Of peculiar interest is the presence of dreikanters in the red beds. The species from the limestone and shale fauna were found by Dr. J. W. Beebe to be largely different from the typical Mississippian fauna, a fact that calls for a basin in which to develop, separated from the Mississippi basin. The species are described and illustrated.

A. E. F.

Address Delivered at the Anniversary Meeting of the Geological Society of London. By W. W. WATTS, president of the society. *Proc. Geol. Soc. London*, Vol. LXVII (1911), 62–93.

Earth history is a history of successive geographies, and of the relation of those geographies to the living beings which successively characterized them. The geological record of any single region is a chronicle of two chief classes of events, a downward movement and uplift. The cycle of deposition is characterized, when uplift is taking place, by a thalassic or deeper water period, a deltaic or shallower period, and a terrestrial period. With resubmergence comes an estuarine period, and later still, a recurrence of thalassic conditions. The conditions in Britain during the Carboniferous period are compared to present conditions in the Gulf of Mexico region, and the British Ordovician geography finds a modern parallel in the Festoon Islands of the Pacific.

The recurrence and non-recurrence of types in cycles of deposition are discussed. Some of the effects of earth movement are seen in the metamorphism and shearing of rocks, its connection with vulcanicity and the formation of ore bodies, and its influences on life.

A. E. F.

The Younger Rock-Series of New Zealand. By P. MARSHALL, R. SPEIGHT, and C. A. COTTON. *Trans. N.Z. Inst.*, XLIII, (1910), 378–407; figs. 9; pl. 1.

Several geologists have described various unconformities in this thick series, yet no two have put them in the same stratigraphical position. Such discrepancies interested the writers to make detailed examinations of these "unconformities," the evidences for which they were unable to find. Correlation with European faunas places the lowermost of the series in the Cretaceous, the prominent limestones in the Oligocene, and the uppermost beds in the Pliocene.

A. E. F.

A Geologic Reconnaissance in Southeastern Seward Peninsula and the Norton Bay-Nulato Region, Alaska. By PHILIP S. SMITH and H. M. EAKIN. Bull. 449, U.S. Geol. Survey, 1911. Pp. 146; figs. 15; pls. 13.

The Norton Bay-Nulato region lies to the east of the southeastern portion of Seward Peninsula. Both areas were little known before this reconnaissance, for they are unimportant in connection with mining. The Nulato-Norton Bay area is largely one of Cretaceous sediments, and the southeastern portion of Seward Peninsula is part of the inclosing rim of older formations. Pre-Silurian formations are present in a highly metamorphosed condition. Less metamorphosed and lying unconformably upon the earlier are Silurian-Devonian-Carboniferous (?) strata. Intrusions and extrusions followed, accompanied by mountain-building and extensive erosion. Cretaceous formations overlie unconformably the preceding rocks, and since their deposition the region has again been subjected to diastrophism of mountain-building intensity. Intrusions followed, and later still extrusions, some of which are rather recent.

Gold placers are very local, and are only in the regions of metamorphic rocks. Gold lode mining has been attempted only in a few places, and has never gone beyond the prospecting stage. Some silver-lead mining had been done to the extent of a few hundred tons of ore. Prospecting for copper has been without success commercially. In the area of Cretaceous sediments coal is generally present, but too thin or too crushed to be of any value.

A. E. F.

Jahres-Berichte und Mitteilungen des oberrheinischen geologischen Vereines. Neue Folge, I, 1911, Hf. 2. Pp. 102; figs. 10; pls. 2; map 1.

Contains many papers by members of the society, among which the following few are of more than local importance:

"Kurze Mitteilungen über tektonische Experimente." By W. PAULCKE. Pp. 56–66; pls. 2. In these pages are given a few results of a series of experiments illustrating mountain-building forces. Strata of different degrees of hardness and subjected to considerable pressure gave, when compressed, overthrust faults, recumbent folds, thickenings and thinnings of the softer layers, and numerous other structures common to the earth's crust.

"Beitrag zur Kenntnis des Rheingletschers und der Talgeschichte der Donau von Sigmaringen bis Ulm." By DR. SCHAD. Pp. 72–92; figs. 6; map 1. Besides a description of the effects of glaciation in this valley, "hanging" drumlins are described as occurring on valley slopes, and are explained as due to the lateral push of subglacial débris up to a point where the thinner overlying ice could no longer move it and therefore overrode it.

A. E. F.

Untersuchungen über den geologischen Bau und die Trias von Aragonien. By ADOLF WURM. *Zeits. d. deuts. geol. Ges.*, LXII, 1911, Hf. 1, pp. 35–176; figs. 17; pls. 7.

Aragon lies in northeastern Spain. The Triassic system lies unconformably on the Paleozoics. It has many similarities with the Triassic of Germany, the names of whose divisions are applied to those of Aragon. The Buntersandstein has a thickness in places of more than 1,700 feet. The Muschelkalk follows with different phases in two different areas, and with a varying thickness the maximum of which is about 250 feet. The overlying Keuper is here composed largely of red and green marls and interbedded gypsum, and also has a varying thickness up to 490–650 feet. Above the Keuper is the Carñiolas, a dark-gray, fine-grained dolomite with a maximum thickness of about 250 feet. Germany has no similar formation. The paucity of fossils leaves the age of the Carñiolas uncertain. In this paper it is considered as probably equivalent to the Lower Lias. A few intrusions of "ophite" is the only representation of Triassic igneous activity. The Triassic fauna and the folded and faulted structure are described.

A. E. F.

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THE DISCONFORMITY BETWEEN THE BEDFORD AND BEREA FORMATIONS IN CENTRAL OHIO[1]

CHARLES S. PROSSER
Columbus, Ohio

CONTENTS

INTRODUCTION

Most of the exposures of disconformity between the Bedford and Berea formations in central Ohio, described in this paper, have been known to the writer for the last eight years. A halftone of one of these outcrops showing the irregular base of the Berea sandstone and the subjacent Bedford shale was published in December, 1904, in the *American Geologist*.[2] Lantern slides of this and other localities, showing similar structure made from photographs taken by the writer and his assistants, are in the collection of the Department of Geology of Ohio State University and have been available

[1] Published by permission of the State Geologist of Ohio.

[2] *American Geologist*, XXXIV, Pl. XIX, Fig. 6, showing contact of Berea sandstone and Bedford shale on bank of Smith Run.

for use by the various teachers during the last five or six years. The writer has used them in his lectures to a succession of classes, while a large number of students have visited one or more of the localities on field trips.

A similar disconformity was found between these formations in northern Ohio and an account of its occurrence at various localities from southwest of Cleveland eastward is contained in *Bulletin No. 15* of the Geological Survey of Ohio now passing through the press. A part of the evidence showing such a disconformity in northern and central Ohio was presented by the writer in a paper entitled the "Contact of the Bedford and Berea Formations in Ohio" at the Ohio Academy of Science meeting in Columbus on December 1, 1911. The part of that paper describing the disconformity in central Ohio makes the following portion of this article. On the day that the writer read this paper he received the October-November, 1911, number of the *Journal of Geology* containing an article by Mr. Wilbur G. Burroughs describing the unconformity between these two formations near South Amherst, Lorain County, in northern Ohio.[1]

Definition of disconformity.—The stratigraphic term disconformity is used in this article as defined by Dr. Grabau "to cover unconformable relation of strata where no discordance of dip exists,"[2] a term that was proposed by him in 1905.[3] For this type of unconformity, which has generally been called unconformity by erosion, Professor Crosby has recently proposed the name *para-unconformity*.[4]

DESCRIPTION OF SECTIONS

In this article only a few of the most interesting outcrops showing the contact of the Bedford and Berea formations on the Westerville and East Columbus quadrangles in central Ohio will be described.

Spruce Run sections.—An excellent contact occurs on the north branch of Spruce Run on the Frank E. Hoover farm, $2\frac{1}{4}$ miles

[1] *Journal of Geology*, XIX, 655–59.

[2] *Science*, N.S., XXIX (May 7, 1909), 750.

[3] *Ibid.*, XXII (October 27, 1905), 534.

[4] *Journal of Geology*, XX (1912), 296.

southeast of Galena and $6\frac{1}{2}$ miles northeast of Westerville. The contact is finely shown for some rods on the northern bank of the stream where the following section was measured:

SECTION ON NORTH BRANCH OF SPRUCE RUN

No.		Thickness Feet	Total Thickness Feet
5.	*Berea sandstone.*—Top of bank. Buff sandstone containing numerous brown spots and composed of rather small grains of quartz sand as seen under lens. The base of the layer somewhat irregular with a tendency to concretionary structure......	$3\frac{2}{3}\pm$	$11\pm$
4.	Zone composed mostly of thin sandstone to arenaceous shale; but with the texture of the Berea. There is, however, a little soft, buff shale. The zone varies in thickness from 7 in. to 1 ft. 4 in.................	$1\pm$	$7\frac{1}{4}\pm$
3.	Buff, quartz sandstone containing many brown spots as weathered. The top of this zone is even; but the base is irregular, making a variation in thickness from 1 ft. 5 in. to 2 ft. 10 in. The under side of this sandstone is irregular and rough as though conforming in shape to the uneven upper surface of the Bedford. The lower part, at least, of this zone is contorted as by concretionary action, so that it has the appearance of a concretionary layer. The disconformity is shown in Fig. 1 of this bank...........................	$2\pm$	$6\frac{1}{4}\pm$
2.	*Bedford formation.*—Bank composed mainly of soft, blue to buff, argillaceous shale with occasional thin layers of sandstone varying from $\frac{1}{2}$ to $1\frac{1}{2}$ in. in thickness. The top of this shale is irregular as though worn by erosion; but in places the thin layers are depressed where the base of the concretionary-like superjacent layer is lowest as though pushed downward by the concretionary action. The thickness of this zone from water level to the base of the concretionary layer varies from 5 ft. 3 in. to 7 ft. 2 in....	$6\frac{1}{4}\pm$	$6\frac{1}{4}\pm$
1.	Farther down the stream and stratigraphically lower than the above zone in the midst of blue, argillaceous shales are blue, hard, compact sandstones, some of them several inches in thickness, which weather to brown, rotten stone indicating the presence of $CaCO_3$.		

A view of this bank is shown in Fig. 1, in which the strips of paper and the hammer indicate the undulating contact of the Bedford and

Berea formations. Above the basal, concretionary sandstone of the Berea, zone No. 3, is the zone of thin sandstone to arenaceous shale, No. 4, above which is the continuous sandstone of zone No. 5, with some concretionary structure in the lower part.

The contact of the Bedford and Berea formations is excellently shown on both banks of the south branch of Spruce Run, one mile

FIG. 1.—Bank on north branch of Spruce Run showing the undulating contact of the Bedford and Berea formations as indicated by the strips of paper and the hammer. Photograph by T. M. Hills.

south of the place just described on the north branch. These banks are not far below the highway on the farm owned by Mr. Frank Merrit of Delaware, now occupied by A. Looker, and about 6 miles northeast of Westerville. The southern bank shows more of the upper part of the Bedford and the following section was measured near its eastern end:

SECTION ON SOUTHERN BANK OF SOUTH BRANCH OF SPRUCE RUN

No.	Thickness Feet	Total Thickness Feet
10. *Berea sandstone.*—Old quarry near the top of the bank which contains layers of buff, fine-grained, quartz sandstone with numerous brown spots when weathered. Some of them are not very hard and weather to a decided brown color. Certain ones		

No.		Thickness Feet	Total Thickness Feet
	have a thickness of 11 in. and some are also ripple-marked. Rather more than 8 ft. of these layers are shown in the wall of the old quarry.........	8+	$40\frac{1}{2}$
9.	Buff, rather fine, quartz-grained sandstone, the layers generally varying from 3 to 10 in. in thickness; but some of them are rather thin or even shaly. It contains grains of marcasite and on weathering shows numerous brown spots.........	$13\frac{1}{2}$	$32\frac{1}{2}$
8.	Thin-bedded to shaly, buff sandstone...........	$1\frac{1}{4}$	19 +
7.	Sandy, buff shale..........................	$2\frac{7}{12}$	$17\frac{5}{6}$
6.	Very fine, quartz-grained, buff sandstone zone, the lower part of which at the eastern end is somewhat contorted, apparently from concretionary action. On weathered surface this sandstone is not dark brown and rotten like the lower sandstones on this bank. The bottom of this sandstone is irregular, conforming to the irregularities in the surface of the underlying shale. This zone is considered the base of the Berea formation and is separated by a line of disconformity from the underlying shale...	$1\frac{3}{4}\pm$	$15\frac{1}{4}$
5.	*Bedford formation.*—Blue, soft, argillaceous shale the upper surface of which is uneven, the zone varying in thickness from 2 to 6 in..............	$\frac{1}{3}\pm$	$13\frac{1}{2}$
4.	Layer of calcareous, blue, very hard, compact sandstone which weathers to a brown color, and the rock becomes rotten. The layer varies from 4 to 5 in. in thickness. It contains $8\frac{1}{2}$ per cent of $CaCO_3$, and $MgCO_3$, which gives it a marked chemical difference from that of the superjacent Berea sandstone	$\frac{1}{3}+$	$13\frac{1}{6}+$
3.	Mainly blue, soft, argillaceous shale; but with an occasional thin, bluish (brownish as weathered) sandstone layer varying from $\frac{1}{2}$ to $1\frac{1}{2}$ in. in thickness	$3\frac{5}{6}$	$12\frac{5}{6}$
2.	Blue, very hard, compact, calcareous sandstone, weathering to a dark-brown color and becoming rotten. It tends to split into two layers and varies in thickness from 1 ft. 9 in. to 2 ft. It is strongly calcareous, containing 26.35 per cent of $CaCO_3$ and $MgCO_3$................................	$1\frac{5}{6}+$	9
1.	Blue, arenaceous and argillaceous shale alternating with layers of blue, hard, compact, calcareous sandstone, varying from 1 to $6\frac{1}{2}$ in. in thickness and some of them ripple-marked. Stream level............	$7\frac{1}{6}$	$7\frac{1}{6}$

In the above section there is a very marked difference in the percentage of calcium and magnesium carbonates in the sandstones which are referred to the Bedford and Berea formations. The following table gives the analysis by Professor D. J. Demorest, of Ohio State University, of samples from zones 2, 4, and 6 of the above section.

	Zone No. 2 ($1\frac{3}{4}$ to 2 ft. Sandstone, 4 to 5 ft. below Zone 6)	Zone No. 4 (4 to 5 in. Sandstone, 2 to 6 in. below Zone 6)	Zone No. 6 (Base of Berea)
	Per cent	Per cent	Per cent
$CaCO_3$	18.75	6.50	0.25
$MgCO_3$	7.60	2.00	0.00
Fe_2O_3	4.00	2.90	1.00
Quartz	52.80	59.10	76.00
Feldspar	4.40	9.30	8.00
Clay	8.40	20.60	14.50

An examination of the above table at once shows the high percentage of calcium and magnesium carbonates in the sandstones of zones Nos. 2 and 4, which are included in the Bedford, and the very small amount, only $\frac{1}{4}$ of 1 per cent, in the basal sandstone of the Berea. The sandstone layer almost at the very top of the Bedford, only from 2 to 6 in. below the base of the Berea or zone No. 6, contains $6\frac{1}{2}$ per cent of $CaCO_3$ and 2 per cent of $MgCO_3$, or a total of $8\frac{1}{2}$ per cent of these carbonates as against the $\frac{1}{4}$ of 1 per cent of $CaCO_3$ in the basal sandstone of the Berea. While in the thicker Bedford sandstone, zone No. 2, between 4 and 5 ft. below the base of the Berea the proportion is still more marked, since it contains 18.75 per cent of $CaCO_3$ and 7.60 per cent of $MgCO_3$, or a total of 26.35 per cent of these carbonates. This shows that more than one-fourth of the entire composition of this sandstone is composed of the calcium and magnesium carbonates, which clearly explains why this stone becomes rotten on weathering and the basal Berea with only $\frac{1}{4}$ of 1 per cent of $CaCO_3$ does not. Again, there is a marked increase in the amount of quartz in passing upward from the Bedford into the Berea, which is 52.80 per cent in zone No. 2, 59.10 per cent in zone No. 4 almost at the top of the Bedford, and 76 per cent in zone No. 6 at the base of the Berea. The percentage of quartz is almost 17 per cent greater in the basal sandstone of the

Berea than in the top one of the Bedford from 2 to 6 in. lower. This marked change in the chemical composition of the sandstones above and below the line of disconformity, together with that structure, is considered as proving that the line of separation between the Bedford and Berea formations occurs at the horizon of this line of disconformity.

The lower part of the above section is shown in Fig. 2. The hammer with the sheet of paper rests on top of the calcareous sand-

FIG. 2.—Southern bank on south branch of Spruce Run showing contact of Bedford and Berea formations. The hammer and sheet of paper mark the $1\frac{3}{4}$- to 2-ft. layer of calcareous sandstone in the Bedford and just above the sheet of paper in the man's hand is the base of the Berea. Photograph by T. M. Hills.

stone, zone No. 2, the upper calcareous sandstone near the top of the Bedford, zone No. 4, is just under the sheet of paper in the man's hand and above it is the basal, concretionary sandstone of the Berea, zone No. 6. Above the basal sandstone in ascending order may be seen the shale of zone No. 7, the thin-bedded to shaly sandstones of No. 8, and the lower layers of the continuous sandstones of No. 9.

On the northern bank, a few rods farther up the stream, is another interesting outcrop, showing the contact of the two formations, only

not so much of the upper part of the Bedford is exposed as on the southern bank.

UPPER SECTION ON NORTHERN BANK OF SOUTH BRANCH OF SPRUCE RUN

No.		Thickness Feet	Total Thickness Feet
6.	*Berea sandstone.*—Old quarries on upper part of bank containing buff-colored, rather fine-grained, quartz sandstone. Lower part of zone partly covered; but apparently continuous sandstone layers of moderate thickness	$25\frac{1}{4}$	$38\frac{1}{4}$
5.	Zone composed in the upper part mainly of arenaceous, blocky shale and in the lower part of contorted, buff, fine-grained, quartz sandstone. The contorted or concretionary sandstone in general varies in thickness from 0 up to 3 ft. 3 in. and even to the entire thickness of the zone. The concretionary or contorted sandstone also occurs at different levels in the shale zone. At two places the concretionary sandstone extends from the top of the Bedford shale clear up to the base of the apparently continuous sandstones, in other words, occupies the full width of this zone. Again a little above the lower end of the bank the concretionary sandstone fails altogether and the rather blocky, arenaceous shales extend from the top of the Bedford up to the base of the continuous sandstone with a thickness of $6\frac{1}{2}$ ft. There is a lithologic difference, however, between the Bedford and Berea shales on this bank, the Berea containing fine grains of quartz sand. The base of this zone is considered the base of the Berea which is separated by a line of disconformity from the subjacent Bedford	$6\frac{1}{2}$	13
4.	*Bedford formation.*—Zone composed mainly of blue, soft, argillaceous shale with an occasional thin, arenaceous lamina. The upper surface is uneven; but near the lower end of the bank the zone is 11 in. thick	$\frac{11}{12}$	$6\frac{1}{2}-$
3.	Blue, very hard, compact, calcareous sandstone, weathering to a dark-brown color and becoming rotten, varying from 3 to $3\frac{3}{4}$ in. in thickness. This sandstone corresponds to zone No. 4 of the section on the southern bank, where it is from 4 to 5 in. thick; but with only from 2 to 6 in. of shale between it and the base of the Berea	$\frac{1}{4}$	$5\frac{1}{2}+$

No.	Thickness Feet	Total Thickness Feet
2. Blue, arenaceous and argillaceous shales with thin layers of blue, hard, compact sandstone from $1\frac{1}{2}$ to 2 in. thick. Several of the thin sandstone layers are ripple-marked. This zone is 3 ft. $10\frac{1}{2}$ in. thick and corresponds to No. 3 of the section on the southern side, which is 3 ft. 10 in. thick	$3\frac{5}{6}+$	$5\frac{1}{4}+$
1. Blue, very hard, compact, calcareous sandstone, weathering to a dark brown and becoming rotten. It splits into two layers and 1 ft. 5 in. is shown to water level at the lower end of the bank. Ripple-marks occur. This zone corresponds to No. 2 on the other side of the run, where it is from $1\frac{3}{4}$ to 2 ft. thick. Stream level	$1\frac{5}{12}$	$1\frac{5}{12}$

Farther down the stream on the northern side is a considerably higher bank which was measured by Mr. Eugene Schmidt.

LOWER SECTION ON NORTHERN BANK OF SOUTH BRANCH OF SPRUCE RUN

No.	Thickness Feet	Total Thickness Feet
7. *Berea sandstone.*—Buff sandstones, the layers of various thickness	$7\frac{1}{4}$	$36\frac{3}{4}$
6. Rather massive, buff sandstone, the lower part with contorted or concretionary structure and the upper part with thinner layers	2	$29\frac{1}{2}$
5. Shale zone with some sandstone, $1\frac{1}{2}$ ft. thick; but in some places apparently thicker	$1\frac{1}{2}$	$27\frac{1}{2}$
4. Contorted or concretionary, buff sandstone zone with shale in middle. At the place measured 2+ ft. in thickness; but not so thick at all places on the bank. Irregular lower surface, forming the base of the Berea sandstone	2+	26
3. *Bedford formation.*—Blue shale with thin layers of sandstone	$3\frac{1}{3}$	24+
2. Blue, sandstone zone which on the edge splits into thin layers, with a thickness of 2 ft. or more. This apparently corresponds to zone No. 1 of the section farther up the run and No. 2 of the one on the opposite side of the stream	$2\pm$	$20\frac{3}{4}$
1. Blue, argillaceous and arenaceous shales with thin layers of blue sandstone from 1 to $4\frac{1}{2}$ in. thick. Stream level	$18\frac{3}{4}$	$18\frac{3}{4}$

Rocky Fork section.—This stream enters Big Walnut Creek not far below Gahanna, and various sections on its banks have been more or less fully described by the writer in former papers.[1] There has been some uncertainty where the line of division between the Bedford and Berea formations should be drawn and in his later papers the base of a concretionary sandstone has been considered as marking this horizon.[2] Later studies appear to support this conclusion and a very brief statement of these additional data will now be given. In former papers a section at the lower end of the gorge, where the basal part of the Berea is shown, and another one farther up the creek on the opposite and eastern bank, where the entire Berea formation occurs, have generally been described. On the western side of the stream, between the two cliffs mentioned above, is another one which will now be described.

SECTION ON WESTERN BANK OF ROCKY FORK

No.	Thickness Feet	Total Thickness Feet
4. *Berea sandstone.*—Buff, quartz sandstone which forms upper part of cliff. Some of the layers are fairly thick; but more of them are thin-bedded....	26	$42\frac{1}{2}$
3. Arenaceous shale changing to thin sandstone at top of zone. This shale is more sandy than that in zone No. 1 of the Bedford. The measurements for this zone have varied from 6 ft. 2 in. up to 7 ft. 8 in., depending upon the amount of thin-bedded sandstone at the top which has been included..........	$6\frac{3}{4}\pm$	$16\frac{1}{2}$
2. Concretionary sandstone stratum composed largely of rather fine-grained, quartz sand. Varies in thickness from 1 ft. 10 in. to 2+ ft...............	2	$9\frac{3}{4}$
1. *Bedford formation.*—The surface is somewhat irregular, indicating a line of disconformity between the two formations. Mainly blue, argillaceous shale with occasional thin layers of compact, blue, calcareous sandstone, which weather to a brown, rotten stone..	$7\frac{3}{4}$	$7\frac{3}{4}$

Samples were taken from a thin sandstone a few inches below the top of zone No. 1 and from the lower part of the concretionary

[1] *Journal of Geology,* IX (1901), 216–18; *ibid.,* X (1902), 274–78; *American Geologist,* XXXIV (1904), 340, 341.

[2] *Journal of Geology,* X, 278; *American Geologist,* XXXIV, 340, footnote.

sandstone, zone No. 2, which have been analyzed by Professor D. J. Demorest with the following result:

	Near the Top of Zone No. 1	Base of Zone No. 2 (Concretionary Sandstone)
	Per cent	Per cent
$CaCO_3$	16.5	1.6
$MgCO_3$	3.8	0.0
Fe_2O_3	5.1	2.0
TiO_2	0.2	0.2
Clay	17.4	11.2
Quartz	48.0	70.0
Feldspar	9.0	15.0

In the above analysis it will be seen that the thin sandstone a few inches below the top of zone No. 1 contains 20.3 per cent of calcium and magnesium carbonates, which a few inches higher in the base of the concretionary sandstone (zone No. 2) decrease to 1.6 per cent. On the other hand, the lower sandstone contains only 48 per cent of quartz, which in the base of zone No. 2 has increased to 70 per cent. The chemical composition of these sandstones, separated by only a few inches of shale, is decidedly different and strongly supports drawing the line of separation between the Bedford and Berea formations at the base of the concretionary sandstone as given above, where it had been placed on structural evidence.

The line of division between the Bedford and Berea formations is not so clearly shown on the next cliff on ascending the stream which is on its opposite side. The base of a sandstone layer varying from 4 to 6 in. in thickness, which in some places has concretionary structure and in others is broken and displaced, has formerly been considered the base of the Berea.[1] The concretionary layer of the lower bank is at about the same level as this sandstone as nearly as can be determined by hand level. Eleven to 16 in. below this 4- to 6-in. sandstone is a thinner one which perhaps should also be included in the Berea formation. The section of the lower part of this bank is as follows:

[1] *American Geologist*, XXXIV (1904), 340, footnote, No. 2 of section, and also see Pl. XVIII, Fig. 3, where the student stands on top of this sandstone.

SECTION ON EASTERN BANK OF ROCKY FORK

No.	Thickness Feet	Total Thickness Feet
5. Gray, fine-grained, quartz sandstone varying in thickness from 4 in. to 1 ft.	$\frac{10}{12}\pm$	6
4. Bluish shales which are quite arenaceous and contain some small sandstone concretions. These shales only slightly resemble those of the Bedford.	$3\frac{7}{12}$	$5\frac{1}{6}$
3. Bluish-gray, compact, fine-grained, quartz sandstone, from 4 to 6 in. thick. This layer in places has concretionary structure and again it is broken and displaced. In former section given as the basal one of the Berea formation.[1]	$\frac{5}{12}\pm$	$1\frac{7}{12}$
2. Blue shales with some thin, sandy layers, the thicker ones ripple-marked. Zone varies from 11 to 16 in. in thickness	$1\pm$	$1\frac{1}{6}$
1. Compact, blue, fine-grained and thin-bedded sandstone which is ripple-marked and is $1\frac{3}{4}$ in. thick. This is a somewhat calcareous sandstone, as may be seen from the analysis, with a texture somewhat like the Bedford sandstones	$\frac{1}{6}-$	$\frac{1}{6}-$

These three sandstones were analyzed by Professor D. J. Demorest with the following result:

	Zone No. 1	Zone No. 3 (Former Base of Berea)	Zone No. 5
	Per cent	Per cent	Per cent
$CaCO_3$	5.1	1.4	0.8
$MgCO_3$	1.8	0.0	0.0
Fe_2O_3	4.4	2.0	2.0
TiO_2	0.2	0.2	0.2
Clay	18.5	13.4	13.0
Quartz	59.0	66.0	66.0
Feldspar	10.0	17.0	18.0

It will be seen from the above analysis that the calcium and magnesium carbonates (6.9 per cent) of zone No. 1 are lower than in the other analyses of Bedford sandstones of this region, while the amount of quartz is not greater than in some of them. In the two higher sandstones the amount of $CaCO_3$ diminishes from 1.4 per cent to 0.8 per cent, while there is no $MgCO_3$ and the quartz has

[1] *American Geologist*, XXXIV (1904), 340, footnote, No. 2 of section.

increased to 66 per cent in each sandstone. It is to be noted that the amount of feldspar in the two upper sandstones is 17 and 18 per cent respectively, so that they may be termed arkose sandstones. These analyses apparently favor drawing the line of division between the Bedford and Berea formations at the same horizon, viz., the base of zone No. 3, as in the former section of this bank. Although the chemical change is not striking, still there is a marked decrease in the carbonates of the sandstones of zones Nos. 3 and 5 as compared with zone No. 1, while the upper sandstones have a larger percentage of quartz than the lowest one.

Smith Run section.—In the northwestern corner of Fairfield County, $1\frac{1}{4}$ miles southwest of Lithopolis and about 4 miles south of Canal Winchester, is an interesting section on Smith Run, an eastern tributary of Big Run. Smith Run is about opposite the Nancy Cole house.

SECTION ON SMITH RUN

No.	Thickness Feet	Total Thickness Feet
6. *Cuyahoga formation.*—Blue, fine-grained sandstones alternating with shales, some of the sandstone layers a foot or more in thickness	$23\frac{2}{3}$	83
5. Two layers of fine-grained sandstone which are conspicuous on the southern bank	$4\frac{1}{3}$	$59\frac{1}{3}$
4. Bluish to light-gray, argillaceous shale which varies in thickness from $5\frac{1}{2}$ to $6\frac{1}{3}$ ft. Two ft. 4 in. below the top of the shale is a $3\frac{1}{2}$-in. layer of sandstone	6±	55
3. *Sunbury shale.*—Thin, tough, even-layered black shale which is well shown in the narrow part of the glen. The measurements vary from $20\frac{2}{3}$ ft. to $26\frac{2}{3}$ ft. Specimens of *Lingula melie* Hall, *Orbiculoidea newberryi* (Hall) Herrick and fish scales occur about $3\frac{1}{2}$ in. above its base and again abundantly at a horizon 4 ft. 8 in. above the base, near the top of the shale bank overlying the last outcrop of the Berea in going up stream	$20\frac{2}{3}$+	49
2. *Berea grit.*—Rather coarse-grained, quartz sandstone which on the weathered surface is much stained, rusty, brownish or even blackish. The upper part contains much marcasite, so that the weathered top surface is pitted and rough, while it is much discolored or blackened. The cliff on the eastern side		

No.		Thickness Feet	Total Thickness Feet
	has a zone of marcasite at the base and it appears to be more or less common throughout the entire thickness. In the small gorge where the run cuts through the formation its entire thickness is shown on each side which varies from 1 ft. 11 in. to about 7 ft. 6 in. Its under surface is uneven, apparently corresponding to the inequalities in the upper surface of the underlying shale. The under surface of the Berea as shown on the western bank is decidedly irregular. From the point where the sandstone is lowest its base, or the top of the Bedford as it is followed up stream, rises 3 ft. 10 in. in a horizontal distance of 21 ft. At the lower end of the cliff where the sandstone has been exposed in recent years by a landslide the base of the Berea rises rapidly from its lowest point to a height of 5 ft. 8 in. and the sandstone is apparently reduced to a thickness of 1 ft. 11 in. In the small gully entering this gorge of Smith Run, just above the western cliff, the Berea is only 2 ft. 7 in. thick; while about 36 ft. farther west on the eastern bank of Smith Run it is about $7\frac{1}{2}$ ft. thick. In all these outcrops it is the lower part of the Berea which thins and thickens, since the upper surface apparently remains uniform with the black Sunbury shale generally shown resting on it. There is no tendency to concretionary structure in the Berea sandstone at this locality and there is obviously a line of disconformity between the Berea and Bedford formations	$6\frac{1}{2}\pm$	$28\frac{1}{2}$
1.	*Bedford shale.*—Soft, argillaceous, bluish-gray to gray shale on bank beneath the Berea sandstone. Farther down the run is chocolate, argillaceous shale which becomes mottled in color toward its mouth. The thickness varies from 22 to 27 ft., depending upon whether it is measured to the lowest or highest point of the under surface of the Berea. Water level of Big Run	22	22

An earlier account of this section was published in the *American Geologist*,[1] together with a halftone of the western bank on which

[1] XXXIV (December, 1904), 344, 345.

the disconformity in the contact of the Bedford and Berea formations is finely shown.[1]

A view of the lowest outcrop of the Berea sandstone, as described in the above section, is given in Fig. 3. The student is indicating the lowest point, stratigraphically, of the base of the Berea which is seen to gradually rise as followed up stream. Below the sandstone is the soft, gray Bedford shale. At the line of the prominent joint in the Berea, a little farther down stream than the student, the base

FIG. 3.—Disconformable contact of the Bedford and Berea formations on Smith's Run. Photograph by H. A. Gleason.

of the Berea rises rather abruptly, so that it is 5 ft. 8 in. higher than its lowest point. The base of this part of the Berea is clearly shown at the left edge of the picture. The top surface of the Berea is uniform all along this bank, showing that there has not been any settling of the blocks along the joint line.

Slate Run section.—About $3\frac{1}{2}$ miles southwest of Lithopolis or three-fourths of a mile northwest of Marcy on the farms of J. M. Hensel and Enos Zwayer in the northeastern corner of Pickaway County, an interesting section is shown along Slate Run.

[1] *Ibid.*, Plate XIX, Fig. 6.

SECTION ON SLATE RUN

No.		Thickness Feet	Total Thickness Feet
5.	*Cuyahoga formation.*—Blue, fine-grained sandstones and some layers of soft, gray shale which contain but little grit. Thin-bedded sandstones with shales and shaly sandstones occur at the base, above which are shales containing concretions....................	25+	69+
4.	Gray, argillaceous shale which is very soft and gritless, with the exception of a 6-in. compact, gray sandstone, the base of which is 3 ft. 2 in. above the bottom of this zone..........................	$8\frac{2}{3}$	44+
3.	*Sunbury shale.*—Thin, black, tough, laminated shale. The sharp contact of this shale with the superjacent, gray, Cuyahoga shale is finely shown in the bed of the run as well as the basal contact at the fall farther down stream with the subjacent Berea. The basal layer of this shale is arenaceous, strongly pyritiferous, and it contains numerous specimens of *Lingula melie* Hall. Different measurements of the thickness of this formation vary from $24\frac{2}{3}$ to 26 ft.............	26	$35\frac{1}{2}$
2.	*Berea sandstone.*—Composed principally of white, quartz sand of moderate coarseness, and forms a single stratum which varies in thickness from a little more than 1 ft. to 5 ft. The upper part contains plenty of marcasite and the weathered surface is pitted from its disintegration; but the surface is horizontal, not undulating. The lower surface is uneven and rough, with ridges which correspond to the thin sandstones in the underlying Bedford, while their faces represent the edges of the layers of soft shale, a character that at this locality Professor Thomas M. Hills first called to my attention. The rapid change in the thickness of this formation and the details of its contact with the Bedford formation are given more fully in the two following more detailed sections at this locality. There is no appearance of concretionary structure in the basal part of the Berea and there is a marked line of disconformity between the Berea and Bedford formations........	5±	$9\frac{1}{2}$
1.	*Bedford formation.*—Mainly bluish, argillaceous shale with an occasional layer of thin sandstone from $\frac{1}{4}$ to 1 in. thick. At lower end of cliff with overlying Berea sandstone 4 ft. 7 in. to water level..	$4\frac{1}{2}$	$4\frac{1}{2}$

Farther down the run are outcrops of the chocolate-colored, argillaceous, Bedford shales. Below these are excellent ones of the black Ohio shale, which in places form banks from 30 to 40 ft. in height. An earlier description of this section was given in the *American Geologist*.[1]

The least thickness of the Berea sandstone noted on this run occurs in the small fall on the Enos Zwayer farm, where the following section was measured at the fall's northern angle:

SECTION OF FALL ON SLATE RUN

No.	Thickness Inches	Total Thickness Feet, Inches
3. *Sunbury shale.*—Basal portion of black, tough shale, the lower layers of which are rather arenaceous, pyritiferous, and tough; but containing near the base specimens of *Lingula melie* Hall and *Orbiculoidea newberryi* (Hall) Herrick	7	2 7
2. *Berea sandstone.*—Upper part not massive and containing much marcasite or iron pyrite. The sandstone in general is composed principally of white, quartz sand of moderate coarseness. The lower surface is rough, conforming closely to the inequalities in the upper surface of the underlying Bedford. At this point the Berea is thinnest and on the southern bank near that angle of the fall it is 2 ft. to 25 in. thick. This difference in thickness of the Berea is at the expense of the upper part of Bedford, since the upper surface of the Berea is even and regular with a dip up stream upon which the Sunbury black shale rests uniformly. Evident line of disconformity at the base	13½	2
1. *Bedford formation.*—Bluish, argillaceous shale with an occasional, sandy layer, approximately ¼ in. thick. Level of stream	10½	10½

A view of this angle of the fall is shown in Fig. 4, in which the lower hammer marks the disconformable contact of the Bedford and Berea formations, and the upper one the conformable contact of the Berea and Sunbury shale. The entire thickness of the Berea sandstone is shown, which is only 13½ in. at the corner or angle. It also clearly shows the thickening of the lower part of the Berea on the

[1] XXXIV (December, 1904), 346–48.

Fig. 4.—Fall on Slate Run showing entire thickness of Berea sandstone with Sunbury shale above and Bedford shale below. Each contact indicated by a hammer. Photograph by W. C. Morse.

Fig. 5.—Entire thickness of Berea sandstone, with Sunbury shale above and Bedford shale below, on northern bank of Slate Run. Upper contact indicated by hammer. Photograph by C. S. Prosser.

northern bank as followed down stream, with the consequent decrease in thickness of the upper part of the Bedford.

On the northern bank, 6 ft. farther down stream than the angle shown in Fig. 4, the Berea has thickened from $13\frac{1}{2}$ in. to 2 ft. and its base is stratigraphically lower than in the angle of the fall and cuts off some of the upper part of the Bedford. This is clearly shown by some of the thin sandstone layers, about $\frac{1}{4}$ in. thick, in the very upper part of the Bedford at the angle of the fall, which are cut off by the base of the Berea as it is followed down stream. Fifteen feet farther down stream from the point where the Berea is 2 ft. thick, it has increased in thickness to 2 ft. 4 in. Twenty feet farther down the run, nearly under the tree, the Berea has decreased from 2 ft. 4 in. to 15 in., and the upper part of the Bedford increased accordingly. This bank is shown in Fig. 5 where the hammer marks the contact of the Sunbury shale and Berea sandstone, below which the upper part of the Bedford shale is shown. At the fence 70 ft. farther down the stream and still on the same side, the Berea has thickened to about 5 ft. It again thins as followed down stream and 20 ft. below the fence at the lower end of the cliff it is only about 1 ft. 8 in. thick. In all this interval the upper surface of the Berea remains about uniform and the differences in thickness are due entirely to changes in its basal portion. The following section was measured at the lower end of the cliff farthest down stream:

SECTION OF LOWEST CLIFF ON SLATE RUN

No.		Thickness Feet, Inches	Total Thickness Feet, Inches
4.	*Berea sandstone.*—Composition similar to that in the other sections at this locality. It is only about 1 ft. 8 in. thick, but thickens rapidly as followed up stream. The lower surface is irregular and rough, corresponding to inequalities in the upper surface of the Bedford formation. No indication of concretionary structure. Conspicuous line of disconformity between the Berea and Bedford formations	1 8	5 3
3.	*Bedford formation.*—Bluish, argillaceous shale with occasional thin, arenaceous layers which a short distance farther up the bank are cut off by the descending base of the Berea sandstone	0 11	4 7

No.		Thickness Feet, Inches		Total Thickness Feet, Inches	
2.	Arenaceous layer to thin sandstone, from $\frac{1}{2}$ to $\frac{3}{4}$ in. thick, which in a horizontal distance of 4 ft. farther up stream is cut off by the base of the Berea. This shows a decrease in thickness of the upper part of the Bedford formation of about a foot in a horizontal distance of 4 ft. This bank is shown in Fig. 6 in which this layer is indicated by the hammer.......	0	1−	3	8
1.	Mainly bluish, soft, argillaceous shale with an occasional thicker and arenaceous layer. Level of water..................................	3	7+	3	7+

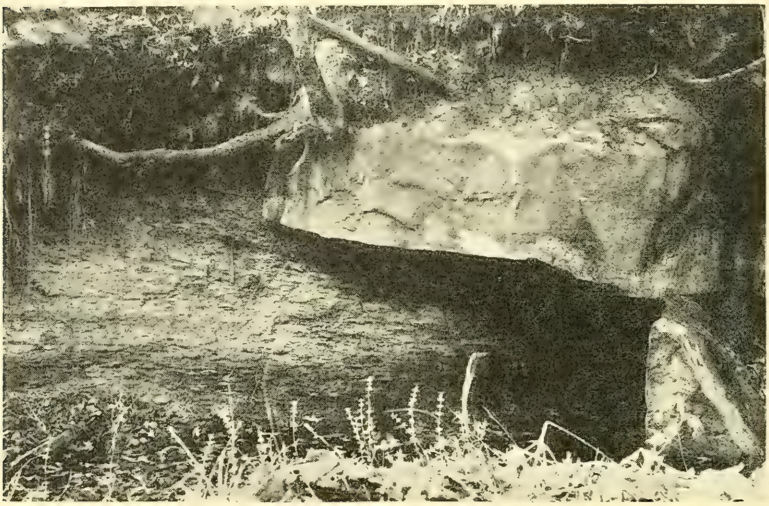

FIG. 6.—Disconformable contact of the Bedford and Berea formations on Slate Run. The hammer marks the thin Bedford sandstone, No. 2 of the section. Photograph by W. C. Morse.

GLACIATION IN THE TELLURIDE QUADRANGLE, COLORADO

ALLEN DAVID HOLE
Earlham College, Richmond, Ind.

PART II

VALLEY OF BRIDAL VEIL CREEK

In elevation this valley ranges from 10,300 feet at the point where Bridal Veil Creek falls into the cirquelike head of the San Miguel valley, to a little more than 13,500 feet, the elevation of the highest peaks on its margin. Above 12,000 feet in elevation it is a broad, flat-bottomed basin a mile or more in width, bounded by cliff walls rising for the most part not more than 200 or 300 feet in height. On this broad, flattened bottom a number of small lakes and ponds occur, lying in rock basins.

Throughout the extreme southwestern part, rock ridges and knobs with rounded surface give character to the topography. Some of the ridges are as much as 50 to 75 feet in height; for the most part, however, the relief is not so great. Some of the rounded surfaces show striae; but in the great majority of cases the general rounded surface is either roughened by unequal erosion or is covered with a layer of small angular fragments, which, in the case of the igneous rocks of this region, easily results from change of temperature. The weathering accomplished since the disappearance of the ice has produced enough soil to support a flora which in the summer months gives a more or less pronounced green color to much of the bottom of the basin.

The south-central part of the basin has a series of tributaries draining numerous small lakes, and flowing north of east to the main stream. Each of these tributaries occupies a level respectively higher than the one next in order to the north, producing in the bottom of the valley the appearance of a series of terraces extending in a direction slightly south of west to north of east.

In the south-central and southeastern part of the basin large angular bowlders up to 15 feet in diameter are scattered over an area of half a square mile or more. These bowlders do not appear to be a part of the talus slope which lies just at the base of the precipitous rock wall which bounds the basin, but, from their somewhat uniform distribution and lack of gradation in size as distance from the cliff face increases, seem to be fragments carried to their present position by the ice. Below about 12,000 feet in elevation the main valley is comparatively narrow, and U-shaped in cross-section.

The channel of the stream in places consists of a narrow gorge 10 to 20 feet deep in the bed rock; in other places it occupies the bottom of the U-shaped cross-section, giving no evidence of having lowered its bed appreciably since the withdrawal of the ice. The amount of post-glacial erosion by the stream may, therefore, be stated as 10 to 20 feet, in the most favorable locations.

The valley is in general well cleaned out; *roches moutonnées*, with abundant striae, are found at many points, the striae being in general approximately parallel to the course of the stream. Some striated surfaces are found on the under side of overhanging ledges which project one or two feet from a nearly vertical cliff face. At about 11,000 feet in elevation, near the trail east of the stream, a striated groove occurs in the nearly perpendicular wall of rock forming the side of the valley. At elevation about 10,700 feet, near the stream, and again a little farther southeast at 11,000 feet, near the trail, pot holes were observed. Each is on the north side of a steep, smooth face of rock in place. The location is such as would result if rock in which a perfect pot hole exists were worn off diagonally across the pot hole, leaving on the steep slope only a trace of the top, while the bottom, still complete, remained wholly back of the sloping face.

Bridal Veil basin has the following tributary basins: (*a*) on the east, (1) East basin, (2) Mud Lake basin, and (3) Gray's basin; (*b*) on the west, (1) Jackass basin, and (2) Silver Lake basin.

East basin.—This basin, above 12,300 feet in elevation, has a comparatively flat bottom and contains a lake lying in a rock basin, which has been converted into a reservoir, increasing its size until

it now has a diameter of nearly half a mile. Northeast of the lake the talus slopes come down to the water's edge; on the southwest, steep, bare slopes of rock in place extend beneath the surface of the water. All along the trail leading into the basin, near the stream, *roches moutonnées* occur. The lake is reported to be 400 feet deep 300 yards from the lower margin; no means were at hand by which to verify or disprove the report.

Mud Lake basin.—This basin is somewhat smaller than East basin. It contains a lake about one-fourth of a mile long and half as broad. An island in this lake, as well as the rock in place on the north side for about 75 feet above the water, shows the rounded outlines of *roches moutonnées*, but no distinct grooves or striae were observed above elevation 12,100 feet. At the head of the basin to the southeast are some rounded knobs of rock in place; but at intervals over the surface angular rock fragments up to 12 feet in diameter appear, partly buried in soil which in the summer is covered with low plants. Beyond this area are the bare talus slopes at the foot of the precipitous bounding walls.

Gray's basin.—Gray's basin is still smaller than Mud Lake basin, and the elevation of its floor is also slightly less, being at 11,900 feet and over. Some rounded, projecting knobs of rock in place occur, but much of the bottom of the basin has enough soil to support a scanty growth of vegetation. In the southeast part of the basin a small rock stream lies at the foot of the talus slope.

Jackass basin and Silver Lake basin.—These basins are characterized by the rounded forms of *roches moutonnées*, and talus slopes sufficiently weathered to support a low alpine flora. Silver Lake basin contains a small lake and has bounding walls less high than the other basins of the Bridal Veil system.

The maximum thickness of ice in the main valley of Bridal Veil Creek was probably not less than 1,200 feet; in the tributary basins, from 200 to 400 feet.

DEER TRAIL BASIN

This basin is a small hanging valley lying more than 1,500 feet above the San Miguel River. Owing to its small size, and its elevation which is on an average perhaps 500 feet less than the

basins tributary to Bridal Veil Creek, the action of the ice was less vigorous. It is like other basins, however, in its flattened profile, in its increased width above the point where it joins the main valley, and in its precipitous bounding walls rising above considerable accumulations of talus. The thickness of ice here was probably from 100 to 300 feet.

VALLEY OF BEAR CREEK

This valley is double headed, and ice from both heads and from La Junta basin on the east united to form the Bear Creek Glacier, about four miles in length. The gradient of the valley, especially toward its head, is steep, locally as much as 1,000 feet per mile. The descent is by a series of precipices. Seen from below (lee side), say from the mill of the Nellie Mine, the valley shows little evidence of glaciation; but seen from above (stoss side), the projecting bosses of rock, and the lower slopes of the valley are obviously smoothed and worn; striae parallel with the course of the valley occur at 9,000 feet elevation. The narrow, deep valley below the upper tributaries is in contrast with the wider and more open basins above. The thickness of the ice which occupied this valley was, at the maximum, more than 1,000 feet.

BASIN EAST OF SAN JOAQUIN RIDGE

The westward-facing slope of Wasatch Mountain shows much talus, and the effect of the ice action is not conspicuous. The eastern part of the basin shows rounded domes of rock of the general form of *roches moutonnées*, but their surfaces are covered with broken rock, and positive signs of glaciation are not evident. Farther west, near the San Joaquin ridge, there are distinct signs of glaciation in the form of *roches moutonnées*, and several ponds in rock basins. The eastern face of the San Joaquin ridge indicates that the thickness of the ice here was not less than 300 feet. The serrate crest of the ridge is in striking contrast with the topography below.

LENA BASIN

Both this basin and its counterpart just west of the base of the San Joaquin ridge are glacial cirques. Both show *roches moutonnées*

in their bottoms, and both have steep descents to the valley below. There is much talus at the bases of the surrounding slopes.

VALLEY OF LAKE FORK

The term Lake Fork is sometimes used to designate that part of the tributary of the San Miguel River from the south which lies above the point of junction with Howard Fork; while that part from the mouth of Howard Fork to the San Miguel River is called South Fork. In this paper, however, the terms lower valley of Lake Fork, and upper valley of Lake Fork, are used to designate, respectively, the portion below and the portion above the mouth of Howard Fork.

LOWER VALLEY OF LAKE FORK

Glacial ice coming down Lake Fork to the valley of the San Miguel not only filled the lower valley of Lake Fork, but spread eastward over the edge of the mesa to a distance of a mile or more from the stream, and together with the glacier in the valley of Bilk Creek entirely covered the mesa between Lake Fork and Bilk Creek for a distance of more than three and one-half miles from the San Miguel River.

The surface of the glacial drift on this mesa is highest toward the northern end, being at a maximum more than 200 feet higher than the outcropping bed rock at the mesa's edge; the surface is lowest just west of the mouth of Turkey Creek, where the drift forms but a thin covering. The ice from Lake Fork passed over the mesa at this point into the valley of Bilk Creek, as is shown by glacial striae on bed rock at the west edge of the mesa, bearing N. 17° W. to N. 24° W. Striae on bed rock at the east edge of the mesa, opposite the mouth of Turkey Creek, vary in direction from N. 3° W. to N. 16° E., the direction of a considerable number being, therefore, approximately parallel to the course of Lake Fork.

The drift on the mesa between Lake Fork and Bilk Creek is arranged in the form of ridges. The highest part of the deposit consists of a ridge about half a mile in length, extending in an approximately north-south direction with a very steep western slope. Southward from this, the ridges have a general northeast-southwest trend, changing at the northeast end to a more northerly

direction. Between these ridges the surface of the deposit is uneven, hummocky, and including kettles occupied in part by small ponds. But although the topography is irregular and uneven, yet the longer dimensions of both the kettles and the elevations are in general parallel to the ridges. The material of the drift on this mesa includes a variety of rocks such as are common to the region; striated bowlders occur at numerous points. The ridges trending northeast-southwest are believed to be due primarily to the action of ice which occupied the valley of Lake Fork; that is, they represent successive positions of the edge of the Lake Fork Glacier as it was finally withdrawing from the mesa, and are, therefore, to be classed as recessional moraines. The north-south ridge near the northern end of the mesa, with its steep western slope, indicates that it, too, was deposited by a glacial sheet from the east. Southward from the lowest part of the mesa as referred to above, the topography is uneven, and not marked by distinct ridges except for a prominent medial moraine three-fourths of a mile long extending from the point of junction of the Bilk Creek and Lake Fork glaciers down to an elevation of about 9,400 feet.

East of Lake Fork, between the San Miguel River and Turkey Creek, the surface of the drift is more or less rough or ridged, the dominant trend of these ridges being parallel to the valley of Lake Fork. The most prominent ridge extends from Vance Creek to Turkey Creek near the eastern edge of the drift, reaching an elevation of more than 9,500 feet at its highest point. North of Vance Creek, while the irregularities of the surface of the drift show distinctly linear arrangement, the ridges are neither so prominent nor so persistent as on the mesa west of Lake Fork.

Southward from Turkey Creek on the east side of the valley for more than two and one-half miles, the topography is wholly irregular and confused. The change in arrangement of the drift is partly due to the greater steepness of the slope on which it lies. From the San Miguel valley to Turkey Creek on the east side of Lake Fork, sedimentary rocks outcrop along the east wall of the valley in a precipitous face below the comparatively level drift-covered area above; but south from Turkey Creek, the sedimentary series

has been worn away to a steep, irregular slope, affording lodgment for glacial débris in greater or less amounts, so that the whole eastern side of the valley from the stream to the eastern limit of the drift presents a steep, irregular surface, with but little change in slope at the elevation corresponding to the edge of the mesa farther north. Landsliding within this area has been noted by Cross;[1] such action is clearly responsible, in part, for the irregular, hummocky topography.

On the west side of Lake Fork, the precipitous face of the sedimentary rocks outcropping below the edge of the mesa extends from the valley of the San Miguel River to about one mile south of the mouth of Turkey Creek. From this point southward for about two miles to the precipice formed by the diorite-monzonite intrusion northeast of Sunshine Mountain, the west slope of the valley, like the eastern, is rough, irregular, and steep, but without precipitous outcrops of rock in place. Unlike the eastern side, however, there is much less glacial débris evident, though rounded pebbles and bowlders, some of them striated, occur at frequent intervals.

In cross-section, the valley of Lake Fork changes from a flat-bottomed, U-shaped form below the mouth of Turkey Creek, to a broadly open, V-shaped form two miles below the mouth of Howard Fork. In general, bed rock in the bottom of the valley is covered with rock waste in the form of alluvium, alluvial fans, or morainal deposits. The alluvial fans are numerous, but comparatively small. Distinct morainal deposits occur only at and a little above the mouth of Turkey Creek—a small recessional moraine, and a fragment of a lateral moraine, respectively.

On the right side of the valley, opposite the junction of Howard Fork with the upper valley of Lake Fork, the drift is found in the form of a well-marked ridge 200 to 300 feet higher than at points above or below. This is clearly another instance of the effect of ice crowding up on the side of a valley opposite to the entrance of a tributary glacier.

The maximum thickness of ice in the lower valley of Lake Fork was about 1,200 feet.

[1] *Telluride Folio*, p. 11.

CIRQUE NORTHEAST OF SUNSHINE MOUNTAIN

The only valley on the west side of the lower valley of Lake Fork which was occupied by a tributary glacier was that one heading in the cirque northeast of Sunshine Mountain. This cirque has practically no exposures of bed rock in its bottom, since the shale which constitutes the underlying formation here weathers readily. In the lower part of the cirque, at an elevation of about 11,000 feet, the slope of the bottom averages about 12°; at 11,300 feet, 20° to 25°; back of this are steep slopes of talus, and above the talus the nearly perpendicular walls of the Telluride formation and igneous rock.

VALLEY OF HOWARD FORK

Howard Fork has but two tributaries that were occupied by glaciers in the more recent epoch, viz., Swamp Canyon and Waterfall Creek. On all sides of Swamp Canyon and its tributaries are found the usual abundant talus accumulations and nearly perpendicular bounding walls. At an elevation of about 11,500 feet, both in the main valley and in the tributary valley on the west, the rounded, smoothed outlines of *roches moutonnées* appear. Striated bowlders were found near the western tributary at an elevation of 11,200 feet. In the lower part of its course the valley shows but little outcrop of rock in place. The maximum thickness of ice in Swamp Canyon was probably from 500 to 800 feet.

The valley of Waterfall Creek has numerous *roches moutonnées* above 11,000 feet in elevation, with striae in some places approximately parallel to the direction of the stream. On the west side of the stream just below the last tributary valley, drift with striated bowlders occurs at 10,750 and at 10,900 feet in elevation. Long talus slopes and cliffs with nearly perpendicular faces form the boundary of the well-cleaned-out valley.

The eastern end of the valley of Howard Fork toward Ophir Pass closely resembles Swamp Canyon in its main features. In the bottom near the stream is a narrow, flattened area, containing a few small ponds; higher up, talus is abundant. The rounded points of exposed rock in place in Ophir Pass indicate that glacial ice was continuous from the valley of Howard Fork over the divide to the east.

Except for deposits about the village of Ophir and near the mouth of Swamp Canyon, the valley of Howard Fork contains but little glacial débris; and of the deposits which may properly be classed as heavy drift that on the north side of the stream near Ophir is partially covered by débris derived from the gullies and ravines cut in the steep southward-facing valley slope. This débris at a short distance north of the stream becomes at the surface at least a true alluvial deposit in the form of a series of alluvial fans, confluent at their lateral edges. The most conspicuous of these fans is that upon which the village of Ophir is built. It has a width (east-west) of about three-fourths of a mile, and its apex is about 400 feet above the main stream at the lower part of Staatsburg Gulch.

In the lower part of the valley near Ophir Station and for a short distance to the east, the valley has the U-shape typical of glaciated valleys, rock in place outcrops at numerous points, and both the rock on the bottom and that on the sides of the valley 200 to 300 feet or more above the stream is rounded, polished, and striated. Eastward from Ophir Station, the entire southward-facing slope of the valley affords but little direct evidence of glaciation; it is furrowed with gullies of sharp V-shaped cross-section down to 10,500 or 11,000 feet in elevation; below this elevation the valleys and ridges are not prominent on the slope. The appearance of a more uniform topography in this lower part is aided by the growth of aspen which is present in some places, and by the alluvial fans which extend across the flattened bottom.

Deposits apparently glacial occur three-fourths of a mile northwest of Ophir village at 10,200 and 10,500 feet in elevation, respectively. On the south side of the valley less than half a mile east of Waterfall Creek, glacial débris with striated bowlders occurs up to about 10,350 feet. Again, on the south side of the stream and west of Swamp Canyon, the surface is covered with glacial drift up to about 11,000 feet. In part it lies in irregular hills, in the form of ridges or benches. This drift includes bowlders in variety, some of them well striated.

The thickness of the ice in the lower part of Howard Fork was probably about 1,000 feet.

UPPER VALLEY OF LAKE FORK

The upper valley of Lake Fork drains a valley proportionately much broader than the other glaciated valleys of the region. As a consequence of its greater width, the action of the ice was less vigorous, and much glacial débris remains. At its maximum a glacier as much as 1,000 feet in thickness moved northward from this valley to join that coming from Howard Fork, as shown by

FIG. 5.—Point below small lake at 11,600 to 11,700 feet, four miles southeast of Trout Lake. Glacial ice passed over this point.

glacial striae on rock in place on the east side at 10,000 feet elevation near the Terrible Mine, glacial débris on the same slope 100 to 200 feet higher, and similar deposits on the west side where the edge of the ice crowded up on the north side of the valley of Wilson Creek, at an elevation of 9,800 to 9,900 feet.

That part of the main valley lying above 10,000 feet in elevation is for the most part well cleaned out. Near the main stream, however, considerable soil has accumulated and supports a forest

growth. *Roches moutonnées* occur at many points above 11,000 feet. Near the pass into the valley of Mineral Creek, at an elevation of 11,900 feet, striae on rock in place bear N. 47° W. Some lakes in rock basins occur, the largest being at 11,600 feet (Fig. 5). Near the margin of the valley the usual talus slopes are found, some of which have weathered until they support sufficient vegetation to give the slopes a covering of green; but for the most part

FIG. 6.—Part of the divide between cirque at head of Trout Lake branch of Lake Fork (on the right), and valley of Cascade Creek (on the left). Elevation of gap in lower central part of view, 12,700 feet. The surface of the glacial ice in the two cirques is believed to have been about up to the lower part of the gap.

the débris consists of apparently unweathered fragments. Fig. 6 shows the steep walls of a part of the southern boundary of the valley.

The eastern slope of the valley, including the tributary valleys from Poverty Gulch to the cirque-valley just above the village of San Bernardo, is steep, irregular in topography, and mostly covered with forest. *Roches moutonnées* occur at a few points, as in

Roger Gulch at 11,200 feet elevation, and in Ground Hog Gulch at 10,900 feet. Glacial drift including bowlders in variety, some of them striated, occur at numerous points, among which may be named: (1) Roger Gulch at 10,200, 10,600, and 10,800 feet; (2) Ground Hog Gulch at 10,500 and 11,100 feet; (3) south branch of Ground Hog Gulch at 10,800 and 11,500 feet; (4) Leslie Gulch at 11,000 feet; and (5) Poverty Gulch at 10,300 feet. Striations on bed rock occur on the south side of the stream draining Poverty Gulch at elevation 10,300 feet, bearing S. 73° W. It is therefore clear that glacial ice covered the whole eastern (westward-facing) slope; the irregularity of the topography is, however, in part due to landsliding, as noted by Cross.[1] The landslide here occurred partly before and partly after the more recent epoch of glaciation. Fig. 7 shows a landslide block which came to its present position before the more recent glacial epoch, as shown by the well-cleaned-out, round-bottomed valley head lying to the northeast of it, the steep walls above the talus, and glacial débris a little farther down the valley. It is in general true that the upper ends of the gulches on the slope here described are cirquelike, have well-cleaned-out, comparatively flat bottoms with occasional ponds, and are bounded by rough, nearly perpendicular walls rising above steep slopes of talus. Rock streams occur on the south side of Poverty Gulch at an elevation of 11,000 to 11,500 feet, and again a half a mile farther south on the other side of the ridge at an elevation of 11,500 to 12,000 feet. The broad cirque lying farthest east on the north side of Sheep Mountain has almost its whole surface below the precipitous bounding walls down to 11,500 feet elevation covered with bare talus slopes; below this a part of the surface supports a forest growth, which in turn gives way to a nearly perpendicular rock face southwest of the artificial lake at 10,000 feet elevation.

The slope south of Trout Lake, like that to the east of the lake, is mostly forest-covered but is less irregular in topography. Due south of Trout Lake, at 10,500 and 10,600 feet elevation, drift with striated bowlders occurs, and hummocky topography including occasional kettles continues to 11,000 feet. Striated bowlders also occur at 10,400 feet elevation southeast of Lizard Head Station.

[1] *Telluride Folio*, pp. 10, 11.

On both the east and the west sides of the central valley on the north side of Sheep Mountain is a medial moraine; on the east side the moraine extends from about 11,600 feet to 11,200 feet in elevation, and is for the greater part of the way a sharp ridge from 15 to 50 feet high; on the west side, the medial moraine is shorter and does not continue to be well marked below 11,400 feet. Besides the drift with striated bowlders already mentioned at 10,400 feet

Fig. 7.—Landslide block of Potosi rhyolite, south of east from Trout Lake Looking north from 12,000-foot point one mile west of Pilot Knob. This block came to about its present position before the more recent glacial epoch.

elevation, the cirque northwest of Sheep Mountain contains deposits of bowlders in variety at 10,500 feet elevation west of the stream and at 10,800 feet more than a quarter of a mile farther east. Since the underlying rock here is shale, no *roches moutonnées* occur. Only the upper 500 feet of this valley is free from forests.

No ice entered the valley from the slopes of Black Face Mountain lying on the west. The upper margin of the ice west of Trout

Lake was a little less than 10,000 feet in elevation; the surface of the ice must, therefore, have had a general slope to the northwest of from 250 to 500 feet per mile, and the moraines about Trout Lake are to be considered as recessional, or as ground moraines.

Trout Lake is practically surrounded by moraines. Cross suggests[1] that the lake may be formed by a dam due to landsliding. While it is quite probable that there has been some movement in the material below the lake of the nature of landsliding, it is also true that so far as sections are exposed in the débris below the lake the deposit is shown to be typically glacial, consisting almost entirely of unstratified drift with bowlders in variety, many of them striated; and since the topography is also such as is found in morainal deposits, that is, irregularly disposed hills and ridges, it seems not inappropriate to class the deposit as morainal even though there may have been some readjustment of the materials since the ice withdrew. On the west and south of the lake there are distinct ridges of drift at several points trending in general in a north-south direction; but much of the surface is quite irregular. East of the lake, the moraine belt is narrow, extending to an elevation not more than 100 to 200 feet above the water's edge. To the southeast, morainal hills are found as far as the upper end of the artificial lake at 10,000 feet elevation. Southwest of Trout Lake they are continuous over the divide into the basin of the Dolores River, and extend up to about 10,400 feet. In this direction small kettles occur. Below the lake (to the north), the moraines continue for one-fourth to one-half a mile at nearly the same elevation as at the lower edge of the lake. Below this morainal dam, just north of the abrupt eastward turn of the railroad, the bottom of the valley is about 100 feet lower, some marshy areas occur, and the morainic hillocks are fewer and much smaller.

Just northeast of the village of San Bernardo *roches moutonnées* occur, and a few rods farther north a low recessional moraine extends from the railroad to the east side of the valley. Sections of this moraine exposed along the railroad show some stratified drift near the top and unstratified lower down, with bowlders in variety, some of them striated. The lower part of the valley just

[1] *Telluride Folio*, p. 10.

above the junction with Howard Fork is steep-sided, V-shaped, with outcropping rock on the east, and slopes covered with talus or soil on the west which, in places, supports a growth of aspen. This forest and the fresh accumulations of talus east of San Bernardo Mountain conceal such signs of glaciation as may have been present, except for occasional patches of bowlders, which, from their rounded and subangular forms and the variety of kinds present, are clearly of glacial origin.

The thickness of the ice in the neighborhood of Trout Lake and in the valleys above was probably on an average not more than 300 to 400 feet, with a possible maximum at some points of 800 feet.

VALLEY OF BILK CREEK

The upper part of the valley of Bilk Creek is double headed, with three small tributary cirque-valleys on the eastern side. Except for the small amount of loose material along the stream in the lower part, and the usual talus accumulations near the upper margins, this part of the valley is well cleaned out. Above 11,000 feet in elevation along the stream draining Bilk basin *roches moutonnées* occur at frequent intervals. At 11,200 feet is a small alluvial flat; below this the stream flows in a channel 100 feet deep at some points. At 11,800 feet and at 12,200 feet in Bilk basin, striae on rock in place have a direction approximately parallel to the course of the stream. At 12,000 feet, and at 12,700 feet, lakes or ponds are found in rock basins. Talus is abundant at the sides and heads of Bilk basin, and on the south side at 11,700 to 11,900 feet is a rock stream. From 11,000 to 11,500 feet in elevation the valley of the south branch of the upper part of Bilk Creek has a more gentle gradient and the bottom is in places marshy. Farther up are *roches moutonnées* and the usual boundary of talus slopes and precipitous rock walls. Abundant talus, partly overgrown with vegetation, flattened bottoms, and walls somewhat less precipitous than in typical cirques characterize the three cirque-valleys on the eastern side.

Magpie Gulch and the cirque lying next to the north contain little direct evidence of glaciation; enough, however, is present to make their occupation by ice certain. Within the lower, forest-

covered portion occasional accumulations of rounded and subangular bowlders in variety occur; in the upper portion, each has the flattened bottom and receding sides which distinguish glaciated cirques from the narrow, V-shaped valleys which were unoccupied by ice. At about 11,000 feet in elevation in the cirque north of Magpie Gulch, the topography is of the irregular form which may in part be due to landsliding. Above this, projecting points of rock in place show well-rounded forms, though no typical *roches moutonnées* occur. The usual long talus slopes and almost perpendicular rock walls form the upper boundary of the cirque. Magpie Gulch is quite similar in its general features; it has, however, a greater length, and contains a much greater accumulation of talus.

Below the mouth of the stream draining Magpie Gulch, glacial drift is present over the greater part of the surface of the valley of Bilk Creek and on the edge of the mesas on either side. In the lower part, however, for a mile or more above the junction of Bilk Creek with the San Miguel River, the drift is not conspicuous; for not only are the sides too steep, for the most part, to afford a place for lodgment for débris, but talus slopes at the base of the cliff faces have formed in post-glacial time, so that drift which may have been left on the less steep slopes nearer the stream has since been effectually concealed. Farther upstream the valley is broader and the products of weathering form alluvial cones and fans, especially on the west side of the stream. Beginning at a point about half a mile north of parallel $37° 55'$ N., and continuing up the valley for four miles, glacial débris is in general abundant near the stream. At the lowest point in the tract just named, the débris is in the form of terraces on the east side of the stream, consisting of unstratified drift as far as observed, with bowlders in variety, some of which are striated. The terraces distinguished are two in number, their surfaces being 20 feet and 40 feet, respectively, above the stream Half a mile farther upstream, on the west side, stratified drift is exposed 100 to 150 feet above the stream. At elevation 9,000 to 9,100 feet morainal hills 40 feet in height occur on the east side of the stream. From this point well-marked morainal deposits, ranging up to 75 feet above the bottom of the valley, extend upstream

on the east side for about a mile and a half; in places the deposit consists of irregular hillocks; in places it becomes a distinct ridge near the stream. On the west side of the stream the moraine is not so well marked; in general, however, a somewhat flattened belt on the western slope corresponds in height to the top of the moraine on the eastern side. At 9,200 feet in elevation the steep slopes of the moraine lie on both sides of the stream. The well-marked morainal deposits do not extend above the alluvial flat lying between 9,200 and 9,300 feet.

The higher glacial deposits on the mesa east of Bilk Creek have already been described. On the edge of the mesa to the west, a forest growth obscures the deposit for much of the first two miles south of the San Miguel River; yet within this area at numerous points exposures of characteristic glacial deposits occur, including bowlders in variety. Farther south and continuing as far as the alluvial flat lying between 9,200 and 9,300 feet in elevation, the surface is covered with drift arranged sometimes as ridges, sometimes as irregular hillocks 50 to 75 feet high, inclosing numerous kettles. On the east side opposite the alluvial flat and for two miles downstream, the slope is shorter and steeper, and the topography is less irregular. One distinct ridge occurs, however, extending from about 9,400 to 9,800 feet in elevation, approximately parallel to the medial moraine already described, and lying about a quarter of a mile farther to the southwest. No distinct lateral moraine is found on the east side except for a short distance opposite Magpie Gulch at 9,900 to 10,000 feet elevation.

The maximum thickness of ice in the valley of Bilk Creek was probably about 1,000 feet.

VALLEY OF CANYON CREEK

That part of the valley of Canyon Creek included in the Telluride quadrangle is almost wholly free from glacial débris. *Roches moutonnées* abound, with striae in places. On the west side of the tributary heading west of Stony Mountain, at 12,000 feet in elevation, striae on bed rock bear N. 43° E. Cross has recorded striae near the Trust Ruby Mill along the north branch of Canyon Creek.[1] The topography of the valley as a whole is extremely

[1] *Telluride Folio*, p. 15.

rough and uneven in spite of the general absence of angular points and sharp lines which is due to the smoothing action of the ice. This impression is heightened by the sharp, rugged lines of the precipitous bounding walls. The summit of Stony Mountain is also very rough; it is, therefore, believed to have stood as a nunatak when the ice was at its maximum. Near the western side of the valley, two rock streams occur, one of which is shown in Fig. 8, and a little lower down, at 12,200 feet in elevation, a small lake in a rock basin.

The maximum thickness of ice in that part of the valley of Canyon Creek included in the Telluride quadrangle was probably not less than 1,500 feet.

CIRQUES NORTH OF DALLAS PEAK

The cirques lying northeast, north, and northwest of Dallas Peak were occupied by glaciers which extended northward to an undetermined distance. *Roches moutonnées*, lakes in rock basins, rock streams, talus slopes, and precipitous bounding walls are present here as in the other cirques of the region.

VALLEY OF DEEP CREEK—EAST FORK

In the cirques tributary to the East Fork, lying north of Iron Mountain and Campbell Peak, talus slopes and rock streams are the chief features. The opposite side of the valley has precipitous rock walls in places at the top, with talus slopes below, extending sometimes 1,000 feet down to the stream. Along the main stream, *roches moutonnées* occur at 10,400 feet in elevation on the south side of the stream, and at 11,000 feet elevation between the two cirques lying north of Iron Mountain.

At elevation about 9,700 feet on the west side of the stream, a small accumulation of glacial débris is found. It extends from the stream to the west talus slope, with its surface about 100 feet above the bottom of the valley. It consists of fragmental and rounded bowlders in variety up to 4 feet in diameter. Small depressions exist between this deposit and the talus to the west. No sign of a similar deposit is seen east of the stream at this point; but there is little opportunity for the lodgment of débris on the east side, as the

cliff bank is precipitous. This deposit extends for a distance of about 30 rods along the stream, and is interpreted as a recessional moraine. At its maximum, the ice in this valley extended to the point where the East and the West forks join, at an elevation of about 8,800 feet. The narrow tongue of ice in which this glacier terminated built a lateral moraine 150 to 200 feet in height and three-fourths of a mile long on the south side of this stream from

FIG. 8.—Rock stream northeast of Gilpin Peak at elevation 12,300 feet. Looking east from col at 13,000 feet. Lake partially hidden from view is in a rock basin. Potosi Peak (outside the Telluride quadrangle) is at center in the background.

elevation 9,500 feet to the west side of the West Fork, where bowlders in variety, some of them striated, mark the farthest extent of the ice. On the point between the two forks is an accumulation of glacial débris below the unglaciated point, and on the eastward-facing slope of the East Fork for half a mile above the junction, glacial débris is abundant; above about 9,500 feet in elevation the surface is covered for the most part with talus from

the steep slopes of the ridge west of the stream. Striae on rock in place occur at 9,300 feet elevation on the east side of the stream, with a direction approximately parallel to the valley's course.

The maximum thickness of ice in this valley was probably about 500 feet.

VALLEY OF DEEP CREEK—WEST FORK

The cirques which supplied the ice for the glacier in the West Fork of Deep Creek lie wholly to the north of the Telluride quadrangle. The glacial deposits in this valley are not in general well marked topographically. Glacial débris, including striated bowlders, occurs in abundance on the west side of the stream at an elevation of from 9,300 to 9,500 feet, and for nearly a mile farther down bowlders in variety appear occasionally at the surface. On the east side of the stream a deposit of glacial drift is found, beginning as a shelf at 9,600 feet, changing to the south into a ridge with a slight depression to the east, and extending to an elevation of 9,250 feet. This ridge contains bowlders in variety up to 6 feet in diameter. The lowest point at which drift occurs on the east side of the stream is at an elevation of about 9,000 feet, where it is found at distances ranging up to 60 or 70 feet above the bottom of the valley. In general, the western boundary of the glaciated area is not well marked, as the distinction along the lower part between the glaciated area near the stream and the landslide area to the west and southwest, east of Hawn Mountain, is not clear.

VALLEY OF PROSPECT CREEK

A small glacier of not more than 200 or 300 feet in maximum thickness occupied the upper portion of the valley of Prospect Creek. In the upper part of the valley rounded, projecting points of rock in place occur, and the appearance at the head of the basin is the same as in the other cirque-valleys of the region; that is, precipitous cliffs in a broad arc at the head with talus slopes below. The valley is broad and flat bottomed in cross-section, though having a steep longitudinal profile. In the upper part some ponds occur, together with several small, level, marshy areas, which are evidently the sites of former basins, now silted up.

In the half-mile just above the 10,500-foot line the surface on both sides of the stream is thickly strewn with large angular or

slightly rounded bowlders up to 15 or 18 feet in diameter. Below 10,500 feet in elevation there are few large bowlders; but rounded bowlders in variety occur down to 10,350 feet. Below 10,500 feet the north bank of the stream is steep and shows no sign of morainic topography; south of the stream, however, the surface is less steep and somewhat irregular. Striated bowlders were found at an elevation of 11,200 feet along the trail east from Bald Mountain, at

FIG. 9.—Turkey basin. Looking southeast from elevation 11,700 feet on Bald Mountain, about one mile distant. Note rock stream below patches of snow.

10,900 feet along the trail on the left side of the stream, and at about 10,400 feet on the left side of the stream.

VALLEY OF TURKEY CREEK

Turkey Creek is formed by the junction of a north and a south fork which drain Turkey basin and Alta basin, respectively. Turkey basin is a broadly open cirque, in general flat bottomed, though containing many low ridges and other irregularities of surface (Fig. 9). It contains three lakes, the largest of which has been increased in size by the construction of dams until it has a diameter of nearly a fourth of a mile. In the southeast part a rock stream

nearly a quarter of a mile in length is found at about 11,500 feet in elevation (Figs. 9, 10, and 11). Talus slopes on all sides, and high, steep, rock walls to the southeast form the boundary of the cirque. Alta basin resembles Turkey basin in its broadly open form, its abundant talus, and steep, high bounding walls. It differs chiefly in having a less level bottom, in the absence of distinct rock streams, and in the much smaller size of its lakes.

Fig. 10.—West edge of rock stream in Turkey basin. Elevation, 11,300 feet. Looking south. Note also the precipitous wall of cirque above talus slope in background.

Ice from Turkey basin and Alta basin spread over the plateau to the west, covering an area about two miles long by one and one-half miles wide. In this area outside of the cirques, below about 11,000 feet in elevation, the topography is that of ground moraine or terminal moraine; numerous irregular hills inclose kettles 10 to 15 feet deep and up to 100 feet in diameter (Fig. 12, and foreground of Fig. 2). In most directions this hummocky topography

continues to the margin of the glaciated area; on the north side, however, a distinct ridge extends for more than half a mile on the south side of Turkey Creek parallel to its course; and north of the stream, at the margin of the glaciated area, a low ridge lies across the valley of the small tributary heading northwest of Bald Mountain. To the southwest, the uneven moraine topography joins the scarcely less uneven landslide topography.

FIG. 11.—Detail of rock stream in Turkey basin. Elevation 11,300 feet. Looking east across north end of the moraine-like surface.

The maximum thickness of the ice in these two basins probably did not exceed 300 to 400 feet.

VALLEY OF BIG BEAR CREEK

Glaciers from the cirques north and west of Wilson Peak, respectively, united and extended down the valley of Big Bear Creek to about 9,300 feet in elevation. The valley of the cirque heading west of Wilson Peak lies, in part, outside of the Telluride quadrangle; its bottom is broad and less even than is the case in

many other cirques of an equal size. Prominent ridges extend from the head for a mile or more to the northwestward, making a series of small, almost parallel valleys in the bottom of the cirque. In each of these small valleys there are rounded projecting points, some talus, and occasional ponds or small lakes. Viewed from below, the slopes leading to the upper part of the cirque appear abrupt, and, in places, rough and precipitous. Below about 10,400

FIG. 12.—Surface of ground moraine, west of Alta basin. Elevation about 10,700 feet. Looking northwest.

feet in elevation the valley of that branch of Big Bear Creek which drains this cirque has prominent moraines. From 10,100 to 10,400 feet in elevation morainal hills are disposed irregularly across the narrow valley, including among them some kettles. On the west, from 10,300 feet in elevation a lateral moraine in places 100 feet high extends northeastward to the limit of glaciation, at about 9,300 feet. A similar ridge lies parallel to the stream on the east side from about 10,200 to 9,600 feet in elevation.

Eastward from these moraines for about two miles the ice spread in a broad sheet, leaving a hummocky, irregular topography. The line of farthest advance of the ice is sinuous, and not marked by any prominent ridges transverse to the valleys; kettles are more abundant, however, near the margin of the moraine than farther back to the south. At different points within the glaciated tract, short ridges of glacial débris with steep slopes occur; but the whole area is covered with a thick growth of spruce and aspen which not only obscures the topography, but often conceals the drift. However, the occasional exposures made by wash of streams, or in the construction of irrigation ditches, furnish abundant evidence of the character of the surface deposits.

An outwash plain of gravel and bowlders extends for about a mile below the edge of the glaciated tract on the east side of the west branch of the stream, having a thickness of from 20 to 30 feet.

The cirque lying north of Wilson Peak resembles closely the one lying next to the east, already described (p. 619). It is broad, shallow, and with unusually high, precipitous walls. As in the cirques just to the east, the underlying rock weathers readily, and *roches moutonnées* and exposed striated rock in place do not occur.

The maximum thickness of the ice was undoubtedly greater in the cirque west of Wilson Peak than in the one to the north, and may have reached 700 or 800 feet.

NAVAJO BASIN AND THE TWO VALLEYS NEXT SOUTH

These three valleys were occupied by glaciers which extended to an undetermined distance beyond the limits of the Telluride quadrangle. That part of Navajo basin included in the Telluride quadrangle is, with the exception of long slopes of talus, almost perfectly cleaned out. *Roches moutonnées* are abundant in the bottom, giving a smooth, regular appearance to the slopes as viewed from the upstream side. As in other cirques, when viewed from the downstream side, a succession of steep slopes appears with some low, rough, precipitous walls.

The cirque next south of Navajo basin is in all essentials like others at equal altitude. The valley is, however, much narrower than Navajo basin, and the talus slopes lying at the foot of the high

bounding walls meet at some points, producing the effect of a valley less well cleaned out. The bottom shows the same alternation of steep and gentle slopes as is found in other cirques.

The second valley south of Navajo basin heads in a shallow, double-headed depression on a steep southern slope. At about 12,500 feet in elevation the generally steep slope is flattened into a shelf or bench perhaps 20 rods in width; back of this shelf the rock wall rises with a steep slope, and on the east and west are short side walls. Below this shelf, talus slopes divided in the middle by a north-south ridge extend down to a second more nearly level area between 11,500 and 11,800 feet in elevation; the topography on this shelf is irregular, and the surface is overgrown with low plants. Below this, steep, rough-faced cliffs appear, at the base of which the more level bottom of the valley begins. The underlying shale is here deeply weathered and eroded in places, showing bare ridges and gullies with but little glacial débris. Farther down the valley, however, glacial drift covers the surface, and a little beyond the edge of the quadrangle typical morainic topography occurs, viz., kettles inclosed by irregular hills containing bowlders in variety, many of which are striated.

At elevation 11,200 feet on the eastern side of the valley glacial drift including bowlders in variety up to 8 feet in diameter forms a ridge extending in a northeast-southwest direction for more than half a mile. The southeast slope of this ridge is gentle, grading off gradually into the unglaciated area; the northwest slope descends to the valley 100 feet or more at an angle of 30° to 35° with occasional exposures due to recent erosion or landslides. This ridge, therefore, constitutes a lateral moraine, the elevation of whose crest above the bottom of the valley is due in large part to the erosion of the underlying formations in which the stream has cut its valley.

The maximum thickness of the ice in Navajo basin and in the valley next south was probably not less than 1,500 feet; in the second valley south of Navajo basin, probably not more than 400 feet.

VALLEY OF KILPACKER CREEK

The cirques at the head of this valley are free from glacial débris. The broader one to the east is cut wholly in a formation of

shale traversed by dikes of igneous rocks. The shale is in places eroded into deep gullies (Fig. 13), leaving bare, gray slopes; in other places landsliding has occurred, resulting in ridges lying

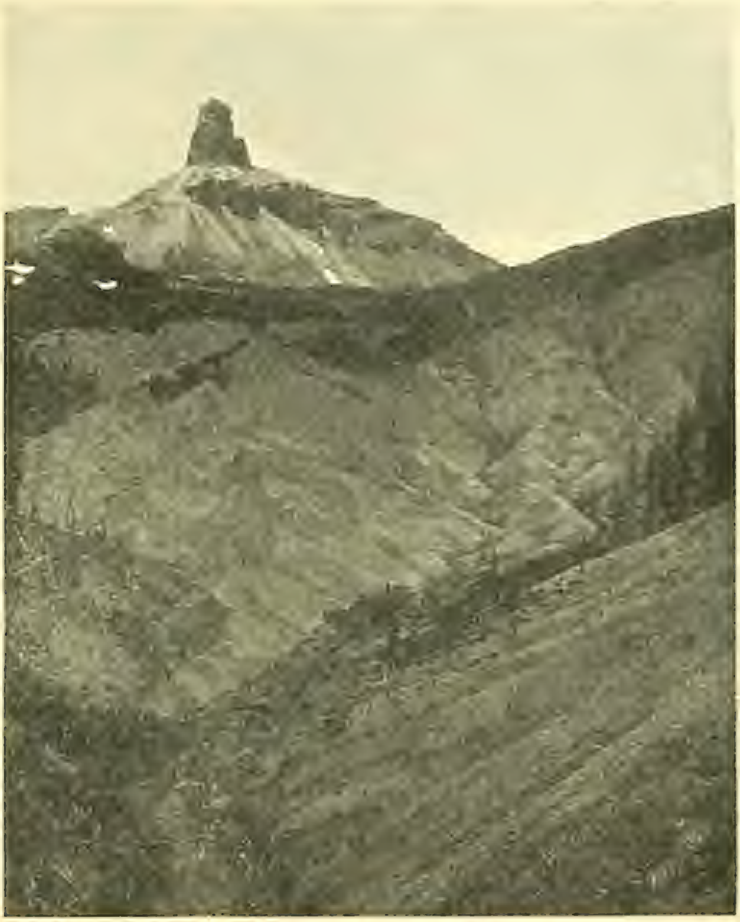

FIG. 13.—East branch of Kilpacker Creek; eroded, bare Mancos shale in center; elevation about 11,300 feet. Lizard Head Peak in background. The eroded floors of cirques with shale as the underlying formation contrast strongly with the *roches moutonnées* of cirques formed in harder rocks.

approximately parallel to the slope, inclosing undrained depressions. The two small cirques near Mt. Wilson have a steep gradient, and

contain some rounded projecting points of rock in place with abundant talus.

From about 11,000 to 10,800 feet in elevation a lateral moraine more than half a mile long lies about a quarter of a mile west of the stream. On the eastern side opposite, there is no distinct ridge of drift, but the somewhat steep slope shows glacial débris at many places. At 10,900 feet in elevation in the bottom of the valley, a small alluvial flat is found, evidently due to the silting-up of a pond. Southwest of this flat the side of the valley is in some places too steep for débris to lie; in other places it is more level, and irregular hillocks inclose kettles. Near the western edge of the glaciated area some landsliding has occurred. In the lower part of the glaciated area abundant glacial débris conceals the bed rock at most points and extends to a height of 300 feet above the stream; bowlders up to 5 or 6 feet in diameter are found, many of them well striated. In the lower half-mile of the glaciated tract the topography of the drift is quite irregular, though some ridges subparallel to the stream occur, as well as a less number of shorter transverse ridges. The lowest point reached by the ice in this valley was at an elevation of about 10,150 feet. Maximum thickness of ice, about 500 feet.

VALLEY HEADING SOUTH OF LIZARD HEAD PEAK

The small cirque lying south of Lizard Head Peak is cut in shale, and its upper part has no glacial drift. The more level part of the cirque ends at about 11,500 feet in elevation; below this for about a quarter of a mile the gradient is steeper and the stream flows for a part of the way in a canyon having for its right wall a precipice of igneous rock, in places 75 to 100 feet high, and for its left wall a steep talus slope.

The lower limit of glaciation in this valley was a little below 10,200 feet in elevation. At this point is a broad transverse ridge of drift 10 feet high, extending from the stream eastward for 100 yards. Another similar transverse ridge, perhaps 15 feet high, occurs 20 rods farther upstream. The slopes of the valley are covered with drift up to 200 or 300 feet above the stream; the deposit on the west side of the stream is apparently more abundant

than on the east, and is partially arranged in ridges approximately parallel to the stream's course.

The maximum thickness of ice in this valley was probably not more than 300 feet.

VALLEY OF WILSON CREEK

The glacier which occupied the valley of Wilson Creek was in the shape of a crescentic sheet concave toward San Bernardo Mountain. A short morainal ridge southeast of San Bernardo Mountain at 10,700 feet to 10,800 feet in elevation marks the lower limit of the ice to the east. Northward, down the valley of Wilson Creek, the ice extended to nearly 10,200 feet in elevation, crossing the stream at this point; above this point is a lacustrine flat which extends for nearly a mile along the stream.

Above timber line to the west are the accumulations of talus and precipitous rock walls usually found in glacial cirques in this region. On the south the slope north of Black Face Mountain is mostly free from talus; some points are smoothed as if by the action of ice, but over most of the surface a thin covering of soil scarcely concealing the rock in place supports a growth of low plants. No precipitous wall is found on the south; the valley slope gradually flattens at the top to form the rounded crest of the ridge, which on its southern side is steep and furrowed with V-shaped gullies. Southeast of San Bernardo Mountain, above the short moraine already mentioned, the glacial deposits show an uneven surface at a few points, inclosing two or three ponds. On the west side of the valley north of east from Lizard Head, a morainic ridge at 10,800 feet in elevation extends for a quarter of a mile in a north-south direction. Over most of the area, however, the surface is irregular.

The lower slopes of the valley on both sides of the stream above the flat are heavily wooded at most points, obscuring to some extent both the topography and the composition of the surface deposits. At numerous points on the eastward-facing and northward-facing slopes, however, glacial drift is exposed, including bowlders in variety, some of which are well striated. In this respect these slopes are in sharp contrast to the southward-facing and westward-facing slopes of San Bernardo Mountain, where rock fragments are

rare, shale exposures abundant, and topography due to landsliding often clearly evident.

The maximum thickness of ice in this valley was probably not more than 200 to 300 feet.

VALLEY OF THE EAST DOLORES RIVER

Glacial ice descended the valley of East Dolores River to an elevation of 9,550 feet. Ice was continuous from this point up the north branch over Lizard Head Pass, up the main valley to the cirques south of Sheep Mountain, and to the top of Flat Top Mountain. Southwestward from Lizard Head Pass, two lacustrine flats mark the position of silted-up lakes. Over most of the remaining surface up to 100 or 200 feet above the stream, glacial drift is abundant. At no point in the Telluride quadrangle was drift found containing a larger proportion of striated bowlders than along the north side of this valley below Lizard Head Pass. The topography on the south side of the stream is more uneven than on the north, but a forest growth has made the determination of the composition of the surface deposits more difficult. The 10,200-foot hill lying in the valley a mile and a half below the pass has a core of igneous rock overlaid by drift. At the point where the stream changes its course to nearly due south, rock in place is exposed on the west side of the stream and drift is not abundant. On the east side, however, morainal hills continue to the junction of the two branches of the stream.

The upper boundary of the glaciated area on Flat Top Mountain is a 25° to 30° slope of bare shale 40 to 50 feet high, extending in an east-west direction for about half a mile. This steep, northward-facing slope lies a little south of the southern boundary of the Telluride quadrangle. From 11,800 to 10,500 feet in elevation *roches moutonnées* are abundant, and in many places show striae bearing northeast of north, in general parallel to the course of the stream. To the northeast, the northwest, and the west, lobes of ice extended to the edge of the steep, precipitous slopes of igneous rock. Along the valley to the northwest, down to about 11,000 feet in elevation, *roches moutonnées* and striae are abundant. The valley leading northward to the Dolores River is a broad ravine in

its lower part, with morainal deposits below about 10,500 feet in elevation. On the east side of the valley a distinct lateral moraine extends from about 10,400 to 9,800 feet elevation, the upper end being farther from the stream than the lower. On the west side a morainic ridge extends from about 10,000 feet in elevation down into the valley of the Dolores River. The glacier on Flat Top Mountain probably did not exceed 200 feet in thickness at the maximum. Its action was not vigorous, and probably only a small portion of the whole mass of ice reached the valley of the Dolores River.

The source of the largest amount of ice entering the valley of the East Dolores River was in the cirques south of Sheep Mountain. Above 12,000 feet in elevation the cirques show the usual variations in gradient, some cliffs from 60° in slope to perpendicular, some slopes more gentle, 10° to 20° with irregular topography due in part to weathered heaps of talus, in part to irregularities of the rock floor. Back of the last more level portion are the slopes of bare talus and the precipitous bounding walls. Below 12,000 feet in elevation the rock in place is largely obscured by weathered rock waste and glacial drift which in places supports a considerable forest growth.

At the point where the stream draining the two cirques enters the East Dolores River, drift hills are abundant on the east side of the river. The edge of the ice here pushed up the valley of the East Dolores to the south for a half a mile, leaving a moraine at 10,250 feet in elevation with its top 30 to 40 feet above the stream. For nearly a mile and a half on the north side of the stream draining the two cirques drift hills cover the slope up to about 500 feet above the stream. In some places the topography is irregular, but more often there are more or less distinct ridges, either approximately parallel to the course of the stream, or tending to become oblique by an approach of the ridge to the stream in the downstream direction. South of the stream the drift hills continue up to about 10,600 feet in elevation. In the drift on both sides bowlders occur in variety, many of them striated. Above the well-marked drift hills, frequent accumulations of glacial débris, in some cases inclosing undrained depressions, continue for a half a mile or more.

In the valley of the East Dolores northeast of Flat Top Mountain drift is abundant on both sides for half a mile or more above the junction of the two branches. Farther upstream, on the west side, the surface is almost wholly covered with talus from the precipitous outcropping igneous rock. On the east side drift is found near the stream below the outcropping cliff face, and in places on the more level area above the outcrop. The westward-facing slope for more than a quarter of a mile above the boundary as determined for the more recent stage of glaciation contains evidence of the presence of ice of an earlier epoch. The line of division between these two areas is, however, drawn somewhat arbitrarily, its position being determined in part by a comparison of the elevations of the limit of recent glaciation at points respectively farther up and farther down the valley. As finally determined the line represents approximately the line of division between abundant drift on the surface (recent epoch) and occasional, disconnected patches of drift (earlier epoch).

The drift hills near the junction of the two branches are, in general, irregular in arrangement, and less prominent below the junction than above. On the north side, however, at 9,900 feet elevation, a distinct lateral moraine occurs extending for 40 rods in a northeast-southwest direction. Lower down on the slope at 9,700 to 9,800 feet elevation is another fragment of a morainic ridge parallel to the one first named. These ridges are distinguished as morainal from somewhat similar ridges and terraces farther up the slope which are due to landsliding, chiefly by their composition, but also by their greater length and regularity. The lower limit of extent of the ice is marked only by small accumulations of drift on the somewhat steep slope. Below this point valley train deposits occur west of the mouth of Kilpacker Creek and again at various points on the south side of the stream up to 30 feet above the bottom of the valley.

The maximum thickness of ice in the valley of the East Dolores was probably about 500 feet.

VALLEY WEST OF GRIZZLY PEAK

That part of the head of the cirque lying northwest of Grizzly Peak on the north side of the stream presents the same features as

the cirques lying south of Sheep Mountain. The slopes on the south side of the stream, however, and the ridge bounding the valley on the south are distinctly different. These slopes are covered with bare talus and show an uneven, hilly topography due to the weathering of numerous irregularly disposed bosses of outcropping rock. The rock in place is completely mantled with angular fragments, and on the west and northwest sides of Grizzly Peak the long, steep talus slopes extend practically to the summit of the mountain, giving to this part of the cirque an appearance which contrasts sharply with the usual precipitous walls which bound most of the other cirques.

Glacial ice of the more recent epoch extended down to about 10,700 feet in elevation. At this point the glacial deposits are best preserved on the north side of the stream, where drift hills 150 feet high show a slope of about 30° both to westward and to southward. For about half a mile eastward on the upper part of the slope on the north side of the stream, drift occurs containing bowlders up to 8 feet in diameter, some of which show striations. Drift with striated bowlders also occurs on the south side of the stream, but a small tributary not shown on the topographic sheet either has prevented the deposition of as large an amount, or has carried away much of what was deposited. The lower part of the glaciated area, up to about 11,500 feet in elevation, is mostly forest-covered. The topography is irregular, with some undrained depressions.

The maximum thickness of ice in this valley was probably about 300 feet.

CIRQUE-VALLEYS TRIBUTARY TO THE ANIMAS RIVER

All the cirques and valleys lying in San Juan County in the southeast part of the Telluride quadrangle are drained by tributaries of the Animas River. With the exception of deposits on the north side of the stream eastward from Ophir Pass and in the lower part of the valley next south, where drift hills with striated bowlders occur up to 400 feet above the stream, these valleys and cirques are all practically free from glacial débris (Fig. 14). In general, abundant talus covers the slopes at the base of steep cliffs, while on the more level portions more or less well-developed *roches moutonnées* are found. In many places the rock in place weathers

too readily to allow striae to be preserved, yet at the following points excellent examples are to be seen:

1. Southeast of Rolling Mountain on the northward-facing slope, numerous striae parallel to tributary streams; average bearing about N. 7° W.

FIG. 14.—Cirque three-fourths of a mile north of Grizzly Peak, tributary to valley of Cascade Creek. Elevation 12,500 to 13,000 feet. Looking south of west from southward-facing slope at head of valley of Cascade Creek.

2. Southward from this slope along the trail over the pass into the valley tributary to Cascade Creek, at 12,500 feet elevation, bearing N. 77° W.

3. South of Twin Sisters Mountain, one-half a mile from the south boundary of the quadrangle, at 12,000 feet elevation, bearing S. 77° E.

4. East side of pass along the trail leading from the Trout Lake branch of Lake Fork to the South Fork of Mineral Creek, at elevation 12,000 feet, bearing S. about 75° E.

5. In the upper part of the valley of Mill Creek, at 12,500 feet elevation, three-fourths of a mile from the eastern boundary of the quadrangle, bearing nearly due east.

Lakes and ponds in rock basins, most of which are of sufficient size to be mapped, occur in the following valleys:

1. Valley of Lime Creek southwest of Twin Sisters Mountain, at an elevation of from 12,000 to 12,500 feet.

2. South Fork of Mineral Creek south of Beattie Peak, at 11,500 to 12,000 feet elevation.

3. Ice Lake basin, at 11,500 to 12,800 feet elevation.

4. Clear Lake, one mile east of U.S. Grant Peak, at 12,000 feet elevation.

5. East of Ophir Pass, at 12,000 feet elevation.

6. Mill Creek basin and cirque next south, at 12,000 to 12,500 feet elevation.

Rock streams are found in the south part of Paradise basin, and to the north and west of Twin Sisters Mountain. In the valley of Cascade Creek at 11,200 feet elevation a small alluvial flat occurs such as is due to the silting-up of a pond or lake.

The maximum thickness of ice in these valleys was in the South Fork of Mineral Creek where it must have reached more than 1,500 feet; the maximum in the valley of Cascade Creek was probably not much less.

ON THE STRATIGRAPHIC POSITION AND AGE OF THE JUDITH RIVER FORMATION

A. C. PEALE

PART II

THE STRATIGRAPHIC POSITION

Hayden, who was the first to note and study geologically the Judith River beds, and to whom the name is due, gives the first published section of them as he found them in the type region near the mouth of the Judith River, following it with a section of the marine strata (Fox Hills) immediately underlying them. Combining these two sections into one we have the following:[1]

HAYDEN'S SECTION OF JUDITH RIVER BEDS[2]

"*Section of fresh water and estuary deposits at the mouth of the Judith River*"

JUDITH RIVER FORMATION

TOP

	FEET
Yellow arenaceous marl passing downward into gray grit, with seams of impure lignite with *Ostrea subtrigonalis*, *Cyrena occidentalis*, *Melania convexa*, and *Paludina Conradi*	80
Impure lignite, containing much sand with Ostrea..........	10
Alternations of sand and clay with particles of lignite; also reddish argillaceous concretions with a few saurian teeth and fresh-water shells	80
Alternate strata of sand and clay, with impure lignite and silicified wood, in a good state of preservation..............	20

[1] *Trans. Amer. Phil. Soc.*, II, N.S., Philadelphia, 1860, pp. 129, 130.

[2] Hayden, according to his habit, constructed his general section from "a large number of local sections" "taken at different points." This is the only section of these beds ever published by him. The type locality is shown on the map (Pl. 8) opposite p. 154, in the area marked "B. L. (Badlands of the Judith)" overlooking the mouth of the Judith River, and is the only locality on the map so marked along the entire course of the Judith River. Hence it must be considered the *type locality*. Professor F. B. Meek says that the Judith River Group was "first examined by him [Dr. F. V. Hayden] at the typical locality near the mouth of the Judith River on the upper Missouri River in Montana."—*U.S. Geol. Surv. Terr.*, IX, p. xlvii.

	FEET
Variable bed, consisting of alternations of sand and clay, with large concretions, with species of Melania, Paludina, Helix, Planorbis, Cyclas, Iguanodon, and Megalosaurus.........	100
Alternations of impure lignite and yellowish-brown clay with Unio, Paludina, Melania, Cyclas, and Lepidotus.........	25
Ferruginous sand and clay, having in the upper part a seam 3 or 4 inches in thickness composed mostly of shells of *Unio*. Lower part ferruginous and coarse gray grit with a seam near the base entirely composed of remains of *Unio Danai, U. Deweyanus, and U. subspatulatus*.....................	100

FOX HILL'S FORMATION

Yellowish and reddish, rather coarse-grained sandstone, becoming deep red on exposure with *Inoceramus ventricosus*, *Mactra alta*, and *Cardium speciosum*....................	20–25
Mixed pure and impure lignite—whole bed containing many crystals of selenite and a yellowish substance like sulphur. The masses of lignite when broken reveal in considerable quantities small reddish crystalline fragments of a substance having the taste and appearance of rosin..........	6–8
Variable strata of drab clay, and gray sand and sandstone. Near the middle there are gray or ash-colored clays with very hard bluish-gray granular siliceous concertions with *Ostrea glabra*, *Hetangia americana*, *Panopea occidentalis*, and *Mactra formosa*................................	80–100

The table given on p. 642 gives the list of species collected by Hayden in the beds [Fox Hills] underlying the Judith River beds as identified by Professor F. B. Meek,[1] together with their outside distribution in other parts of Montana, the Dakotas, and Colorado. In the last column is shown the recurrence of these species in Stanton's Claggett formation, which apparently occupies the same position in relation to the Judith River beds, including without doubt the beds shown in Hayden's section, which are identical with the sandstones found by the writer at the top of the dark Pierre shales and below the lighter-colored clays, sands, and shales of Judith River age. In these lower sandstones invertebrate fossils of Fox Hills age were found.

[1] *Report U. S. Geol. Surv. Terr.*, IX (1876), 1–506.

Fox Hills Species from Mouth of Judith River (Immediately underlying Judith River Beds)	Distribution in Fox Hills of Other Localities: *Wyoming* near Parkman and in Converse County	North and South *Dakota* Mainly on Indian Reservations	*Colorado* Denver Basin and Eastern Colorado	*Colorado* Mainly on White River in North-Western Colorado	From Claggett Formation as described by Stanton (immediately underlying Judith River Beds)
Inoceramus pertenuis	..	..	..	×	..
Inoceramus crispii cubcompressa	..	..	..	..	..
Mytilus subarcuatus	..	..	×	..	..
Tancredia americana	×	×	×	..	×
Cardium (Cricocardium) speciosum	×	..	×	×	×
Callista (Dosiniopsis) Owenana	..	..	×	..	..
Tellina (Peronaea) equilateralis	×	..	×	..	..
Mactra (Cymbophora) formosa	..	..	×	..	×
Mactra (Cymbophora?) alta	..	..	×	×	..
Pholadomya subventricosa	..	..	..	..	×
Thracia subtortuosa	×	..	..	..	..
Thracia gracilis	..	..	×	..	×
Thracia (?) prouti	..	..	..	..	..
Liopistha (Cymella) undata	×	..	×	..	×
Glycimeris occidentalis	..	..	..	..	..
Lunatia subcrassa	×	×	×	..	×
Vanikoropsis Tuomeyana	..	..	..	..	×
Baculites asper	..	..	..	..	..

Stanton's Section on East Side of Cow Creek

		Feet
Judith River Beds	Middle portion covered in bed of creek. One hundred and fifty feet of lower Judith River beds are continuously exposed in the upper section, and one-half mile east, where the Judith River beds are horizontal, a thickness of 490 feet was measured, but the base is not exposed at this point. A shale bed about 30 feet above the base of the formation yielded many leaves of *Trapa (?) microphylla,* together with abundant fresh-water Mollusca, including *Sphaerium recticardinale. Physa copei (?), and Goniobasis subtortuosa.* Another horizon about 300 feet from the top, in the exposure one-half mile east of the section, yielded *Sphaerium planum, Anodonta propatoris, Unio danae (?), Unio primaevus, Valvata montanaensis, Hyalina? evansi, Hyalina(?) occidentalis, Planorbis amplexus, Physa copei Goniobasis subtortuosa,* and *Goniobasis gracilenta*	490

		FEET
Claggett Formation	*c*) Light-colored shales or sandy clays with band of brown sandstone containing *Tancredia americana* in middle. Top of marine	50
	b) Yellowish-brown sandstones, generally soft, but with harder layer and lenses, with *Tancredia americana, Cardium speciosum, Tellina equilateralis, Liopistha* (*Cymella*) *undata, Lunatia, subcrassa, Baculites* sp., and fragment of vertebrate jaw	20
	a) Dark shales with concretions bearing *Baculites ovatus, B. compressus, Nucula cancellata, Leda* (*Yoldia*) *evansi*, and *Gervillia borealis*. These shales weather much as the Bearpaw, but with a reddish tinge. The concretions are different with fewer fossils and not so great a variety. These beds become lighter toward the top, the upper 50 feet containing two seams of thin brown sandstone, each 2 to 3 feet thick	300–400
	Total thickness of Claggett	370–470
Eagle Formation No fossils	*e*) Cross-bedded and finely laminated sands with thin seams of lignites, in places becoming more massive	125
	d) Very light-colored, fine, heavy-bedded sandstone	40
	c) Heavy-bedded buff sandstones, soft at base, but harder above, and with indurated lenses and numerous large concretions, weathering brown at the top. The thickness of *b* and *c* is very variable	50
	b) Heavy-bedded buff sandstones with lenses of lignite and shales sometimes exhibiting cross-bedding	30
	a) Regularly-bedded buff sandstones with several thin seams of dark shales	20
	Total thickness of Eagle formation	265
Dark Benton Shales	Baculites and other invertebrates in concretions, and containing several layers of sandstones in upper 100 feet. The following fossils were found in these shales near the base: *Inoceramus* sp., fragments of a thick-shelled form; *Prionotropis*(?) sp., fragment; *Scaphites ventricosus; Baculites* sp., a slender, strongly nodose form. Several genera of invertebrates not specifically determinable were collected in the upper portion	300

The section by Stanton and Hatcher was made north of the Missouri in the disturbed region, but is apparently the normal section corresponding closely to those taken by us on the Judith River, at several places south of its mouth. As published, however, 500 to 700 feet of supposed Bearpaw shales, including light-colored sands and shales at the base, are added by Stanton above the Judith River beds. These have not been included by us as they were not in his section as shown one mile below their camp but were *added from exposures noted west of their camp.*[1] In some of his localities, as on the Birch Creek, he says:[2] "The overlying Bearpaw shales are not represented in this immediate region, having been entirely removed by erosion." In other places what *appear* to be Pierre shales seem to overlie the Judith and there is little doubt that in some cases they do actually occur at higher levels, as we saw at Mauland, but until a careful areal survey is made of the whole region it will be impossible to say whether the beds are below and of Belly River age, or whether the case is as at Mauland, where the cause of the apparent superposition is one of the numerous faults traversing the region. In Dr. Stanton's section given above there is no doubt but that 70 feet or more of the beds referred to the Claggett are of Fox Hills age, while the 300–400 feet of dark shale immediately below should be referred to the Pierre. These shales, Dr. Stanton says, "weather much as the Bearpaw" and contain concretions containing Pierre fossils. Stanton and Hatcher[3] say in their description of the Claggett:

> In the neighborhood of Judith (old Fort Claggett), where they are well exposed, they have a total thickness of about 400 feet and consist largely of dark clay shales with variable intercalated bands and beds of sandstone, especially in the upper half. The dark shales of the lower part of the formation contain many calcareous concretions, which yield *Gervillia borealis, Baculites ovatus, Baculites compressus,* and a few other forms, elsewhere regarded as characteristic of the Fort Pierre. The yellowish sandstone beds higher in the formation, especially one about 200 feet from the top and another near the summit, are often locally very fossiliferous, and bear an invertebrate fauna, of which the most conspicuous species are the following:

[1] *Bull. U.S. Geol. Surv., No. 257,* p. 44.

[2] *Ibid.*, p. 40.

[3] *Ibid.*, p. 13.

Species from Upper Part of Claggett Formation

Tancredia americana	Mactra formosa
Cardium speciosum	Mactra alta
Sphaeriola ? endotrachys	Lunatia subcrassa
Tellina equilateralis	Vanikoropsis tuomeyana
Thracia gracilis	Baculites sp.
Liopistha (Cymella) undata	

This has long been considered a typical "Fox Hills" fauna, and a number of its species do recur at the top of the marine Cretaceous immediately below the Laramie in Colorado and elsewhere.

The table already given of the Fox Hills fauna lying below the Judith River contains a list of 18 species of which four, so far as the writer can learn, have not yet been found elsewhere in the Fox Hills. Out of the remaining 14, 10 have been collected in the Fox Hills beds of eastern Colorado, while 8 have been found in the Claggett of Stanton, which seems not only to contain a "typical Fox Hills" fauna but also to hold the same stratigraphic position. The Fox Hills beds of Canada occupy the same position also, but they are, according to Dawson, McConnell, and Tyrrell, so inconstant that they have been considered as a whole with the Pierre and the two faunas have not been differentiated.[1] This inconstancy of the Fox Hills beds, especially so far as thickness goes, has also been everywhere noted south of the international boundary line, ranging from nothing (that is, in some places the overlying beds—Lance and Judith River—rest on the Pierre shales) to 800 or 1,000 feet. This last is the thickness in the Denver basin of Colorado as given by Eldridge.[2] In one place only, in Colorado, does it fall much below 1,000 feet. This is at Golden, where the thickness is only 500 feet, which Eldridge attributes to the non-deposition of the lower part. This thickness of 500 feet is about the same as noted by us in 1910 in south-central Wyoming. As to the shells in this Colorado section Eldridge says:[3]

While the invertebrate fossil remains occur throughout the entire thickness of the Fox Hills, there is an especially conspicuous array of characteristic forms at the very summit of the formation, in the uppermost layer of the capping sandstone, none of which is ever found above, and but few of which are met with in numbers below.

[1] *Contribution to Canadian Paleontology*, I, 29.

[2] *Monographs U.S. Geol. Surv.*, XXVII (1896), 71.

[3] *Ibid.*, p. 72.

In the table already given, of the species listed in the column under "Denver Basin and Eastern Colorado," more than half the number came from the very summit of the formation where there is no admixture of Pierre forms. Curiously enough, too, the list for the beds below the Judith River in Dr. Stanton's section on east side of Cow Creek (see pp. 642–43) suggests no mingling of Pierre and Fox Hills forms, such as is so clearly shown in the collections made on the Yellowstone River about 150 miles above its mouth.[1] Whether this indicates a condition in the Judith basin similar to that noted by Eldridge at Golden will have to be left to the result of future careful study of the Fox Hills outcrops. It is more than likely, however, that, as stated by Professor Meek:[2] "These beds underlying the brackish-water lignite [Judith River] beds form an upper member of the Fox Hills group."

The mingling of the Fox Hills and Pierre faunas has been noted, but to a more limited extent, also in the Dakotas where, however, as we have indicated, the entire thickness of the Fox Hills is not seen. Indeed, it is questionable whether a full development of the formation occurs anywhere in this area. At the top of the Fox Hills sandstone, which has a marine fauna, Dr. Stanton found a thin and widely distributed bed with a brackish-water fauna which he regards as belonging to the Fox Hills rather than to the overlying Lance formation, an interpretation that is not in accord with the views of the field geologists studying the area, who placed it immediately above the unconformity which marks the contact of the Lance on the Fox Hills.[3] Similar brackish-water faunas are found, according to Dr. Stanton, wherever the Judith River formation is found "intercalated in the upper and lower portions of the formation."[4] This occurrence, just referred to as at the base of the Lance formation, is on the line of the unconformity which,

[1] *Report U.S. Geol Surv. Terr.*, IX (1876), p. xxxiv.

[2] *Ibid.*, p. xxxvi.

[3] *Amer. Jour. Sci.*, XXX (September, 1910), 178.

[4] *Bull. U.S. Geol. Surv., No. 257,* p. 120.

The entire quotation is: "The brackish fauna has a wide geographic distribution occurring in practically every area in which the Judith River formation is found, but it is confined to thin beds intercalated in the upper and lower portions of the formation."

according to Knowlton,[1] is so widely recognizable. Referring to this mingling of forms at the base of the Lance, Knowlton says:[2]

> Because Fox Hills fossils occur in the lignitic shales at the base of the "somber beds" and mingled with the brackish-water types of the Lance formation is not necessarily proof positive that the various faunas lived at the same time; for if the deposition of the Fox Hills was followed by a definite erosion interval, what is more probable than that in the deposition of succeeding strata fossil shells would be eroded from the marine beds and carried into channels, there to mingle with the then living brackish-water fauna of the Lance formation?

A reference, at this point, to the Canadian section will be of interest as proving the existence of two series of fresh-water beds, the lower one of which was named the Belly River series by Dr. G. M. Dawson in 1882.[3] He had previously described in his report on the geology and resources[4] in the vicinity of the 49th parallel an upper series of fresh-water badland beds lying south of Wood Mountain, which he referred to the Lignite Tertiary and an underlying series thought to correspond to the Fox Hills group.[5] By the Lignite Tertiary, Dawson meant the Fort Union group of Hayden; and he also correlated the beds with the Judith River beds. The same beds are later described as the Laramie (Edmonton and Paskapoo) by the other Canadian geologists.

Later in his last report,[6] without having revisited the region south of Wood Mountain, Dawson relegated these beds to the Belly River series, and says: "The beds thus separated as the Belly River series were, in 1875, by me, correlated with the Judith River series of the Missouri." Dawson had evidently been misled by the lithological resemblance between the two series. On p. 117*c* of the report just cited he says: "The Belly River series has

[1] *Proc. Wash. Acad. Sci.*, XI (1909), 170–238;. *Jour. Geol.*, XIX (1911), 360–776.

[2] *Ibid.*, p. 365.

[3] *Geol. Surv. Canada, Report for 1880–82*, Montreal, 1883, pp. 1B–8B. On p. 1 reference is made to a note published by Dawson in May, 1882, in which he says "the following report is essentially a reprint."

[4] *British North American Boundary Commission Report on the Geology and Resources in the Region in the Vicinity of the 49th Parallel*, Montreal, 1875, pp. 103–58.

[5] *Ibid.*, p. 156.

[6] *Geol. Surv. Canada, Report of Progress, 1882–84*, Montreal, 1885, "Report of the Region in the Vicinity of Bow and Belly Rivers, 1884," pp. 118*c* f.

not yet been definitely identified in any part of the disturbed belt bordering the mountains, where, from the complicated character of the sections and absence of fossils, it is difficult to discriminate between it and the lithologically similar beds of the Laramie." By Laramie, Dawson meant the beds which overlie the Fox Hills Cretaceous, including his Porcupine Hills and St. Mary's series, or, as the Canadians name them later, "Paskapoo" and "Edmonton." As Dawson says,[1] it is not intended by its [Laramie] use to differentiate the beds so named from those of the Judith River and Fort Union series, with which they may be found to blend as the intervening district is more completely explored. That Dawson was not himself satisfied is shown by the fact that in the same report, pp. 125, 126, he suggests an alternative explanation which involves the existence of an unconformity at the base of the Judith River formation. The evident confusion in trying to differentiate between these "Laramie" beds (Dawson) and the Belly River beds was not cleared up until more complete stratigraphic examinations were made by R. G. McConnell[2] and J. B. Tyrrell.[3]

McConnell, when considering the stratigraphical position of the Belly River beds, writes as follows:[4]

> The doubt which existed at one time in regard to the stratigraphical position of the Belly River series, on account of the Laramie *facies* of its invertebrate fauna, has been removed by a more complete examination of its eastern margin. Its line of contact with the Pierre has now been traced, through a distance of over 150 miles, by numerous exposures, all of which afforded the clearest possible proof of its subordinate position. The junction is marked in many places by low plateaus (see p. 41), which offer exceptional facilities for noting the relations of the two formations, as they owe their origin directly to the superposition of a protecting covering of the less easily eroded dark shales on the light-colored beds below. The western slopes of these plateaus are usually bare, and the line of contact between the two dissimilarly colored series distinctly drawn. A reference to the general section which accompanies the map will also show that at the west end of the Cypress Hills, the Laramie and Belly River series, separated by the Pierre shales, occur in what is practically the same section, and as the beds have been so little disturbed that their maximum dip seldom exceeds ten feet to the mile, and consequently no question of over-

[1] *Geol. Surv. Canada, Report for 1880–82*, Montreal, 1883, p. 2B.

[2] *Geol. Surv. Canada*, I, "Report for 1885," Montreal, pp. 1–85*c*.

[3] *Ibid.*, II, "Report for 1886," Montreal, pp. 1–176*e*.

[4] *Ibid.*, p. 64*c*.

turn or dislocation is involved, no better stratigraphical evidence can possibly be offered.[1]

Tyrrell's work in 1886[2] was in the northern part of Alberta and the western edge of both Assiniboia and Saskatchewan on drainage tributary to Red Deer River, Ghost River, Bow River, and both the North and South Saskatchewan. His section in this area from the Belly River series to the Laramie, including both, is as follows:

	FEET
Laramie	
Paskapoo Series: Gray and brownish weathering, lamellar or massive sandstones, and olive sandy shales. This is an exclusively fresh-water deposit................	5,700
Edmonton Series: Soft whitish sandstones and white or gray, often arenaceous, clays, with bands and nodules of clay, ironstone, and numerous seams of lignite. These are of brackish-water origin and correspond to the lowest portion of the St. Mary River series of Dr. Dawson's Report (*Geol. Survey Report for 1882–84*, p. 114*c*)	700
Fox Hills and Pierre	
Brownish weathering sandstones and dark gray clay shales	600
Belly River Series	
Soft, whitish sandstones and arenaceous clays, changing toward the east to light-brownish and yellowish sandstones and sandy shales, bottom not seen............	

From what we have detailed in the preceding pages, it seems impossible to avoid the conclusion that the stratigraphic position of the Judith River beds is *above* the Fox Hills sandstone which in turn rests on the Pierre shales. The Judith River thus holds exactly the same interval in the geological column that is occupied by the Lance formation and not that of the Belly River series of Canada, nor that noted for their equivalent beds in the United States. The lithological resemblance between the beds of the Belly River series and the Judith River formation does not count for much and is no greater than that between the Lance formation and the Judith River beds. Dr. Stanton,[3] referring to the Belly River series, says:

[1] Mr. McConnell in reply to an inquiry makes the following statement to the writer: "I have had no reason to change my mind in regard to the relative positions of the Belly River and Pierre formations as given in the report you refer to. I have not done any work in recent years on the plains, but the work done by others of the Survey has all been confirmatory."

[2] *Geol. Surv. Canada*, II, "Report for 1886," Montreal, p. 5*e*.

[3] *Bull. U.S. Geol. Surv., No. 257*, p. 26.

R. G. McConnell and J. B. Tyrrell confirmed Dr. Dawson's conclusions concerning the stratigraphic position of the Belly River series so far as the overlying beds were concerned but still left the exact age of the underlying formation undetermined.

They could hardly have done otherwise as their sections in both cases did not go to the base of the Belly River series, but in the Saskatchewan and Peace River districts Benton shales[1] were found by Dr. G. M. Dawson below the Niobrara, to which latter formation Dawson and the other Canadian geologists referred the beds afterward relegated to the Belly River series. It was here that the Dunvegan sandstones, which lie above the Benton, were named; and these Dunvegan sandstones Dawson was always inclined to correlate with the Belly River series. The flora of this Dunvegan series, which Sir William Dawson says is very nearly akin to that of the Dakota group, "accords with the stratigraphical position assigned the beds, namely below the horizon of the Fort Pierre Cretaceous."[2] The following section is given by Osborne on p. 9, in Vol. III, Part II, of *Contributions to Canadian Paleontology:*

PROVISIONAL CORRELATION

Fresh water Brackish and fresh water	Paskapoo* (no dinosaurs) Edmonton	Ft. Union† Laramie and Judith River	 Triceratops, Torosaurus, Dryptosaurus, Ornithomimus
Marine	Pierre-Fox Hills Group	Fox Hills Fort Pierre	
Fresh and brackish water Sandy clays and sandstones	Belly River 910 feet	Montana exposures in part (Niobrara)	Stereocephalus, Monoclonius, Ceratops, Trachodon, Deinodon, Ornithomimus, Compsemys, Ptilodus
	Ft. Benton	Ft. Benton Dakota	

* Regarded by Tyrrell as the beginning of the Tertiary.
† Mammals of Puerco type discovered by Douglas in 1901.

[1] *Geol. Surv. Canada, 1879–80,* Montreal, 1881, p. 133B.

[2] *Ibid.*, pp. 119–23B.

There is, therefore, little, or no doubt as to the beds underlying the Belly River series in Canada. On our side of the line, we were fortunate enough to see complete sections from the Jurassic up into the Fort Union on Fish Creek, where the Belly River beds lie above the Eagle sandstones with an intervening alternation of sandstones and sandy shales that could not in any way be confounded with the characteristic soft dark shales of the Pierre that rest on the horizontal fresh-water badland bed of Belly River age.

COMPARATIVE SECTIONS SHOWING RELATIVE POSITION OF BELLY RIVER AND JUDITH RIVER FORMATIONS

		Colorado and Wyoming		Montana			Canada
		Eastern Colorado	Wyoming	Judith River Section	Fish Creek Section	Willow Creek Section	
Eocene Tertiary	Ft. Union		Upper Fort Union		Fort Union	Fort Union	Paskapoo
			Lower Fort Union (Lance)	Judith River	Lance	Lance	Edmonton
	Shoshone	Denver			Livingston	Absent	
		Arapahoe					
Upper Cret.	Lara.	Laramie	Laramie	Absent	Absent	Absent	Absent
	Mont.	Fox Hills	Fox Hills	Fox Hills	Fox Hills	Absent	Fox Hills
		Pierre	Pierre	Pierre	Pierre	Pierre	Pierre
L. Middle Cret.	Colo.	Niobrara	?	Belly River Eagle	Belly River Eagle	Belly River Eagle	Belly River Dunvegan
		Benton	Benton	Benton	Benton	Benton	Benton
	Dak.	Dakota	Dakota?				Dakota?
Lower Cret.		Comanche		Kootenai	Kootenai?		Kootenai
		Morrison		Morrison	Morrison		

In the accompanying correlation table of local sections the line of unconformity between the Cretaceous and Tertiary is shown by the double line, which, in Colorado, indicates the break between the Arapahoe and the Laramie, and in other localities represents the erosional interval between the Lance and Laramie wherever the two are in contact as seen by Dr. Knowlton and the writer on the North Platte River near the mouth of Medicine Bow River in Wyoming. It marks also the greater stratigraphic hiatus noted in all sections made up to the present time in Montana where the Laramie is absent; and where either the Lance or the Judith River is in contact with the Fox Hills or where this also is absent with the Pierre, all of these conditions are shown graphically in this section. The sections in the Dakotas are not given, but there, as already stated, the Lance is sometimes in direct contact with the Pierre, as in the section given for Willow Creek, Mont., or with the FoxHills beds, the thickness of which varies according to the amount that has been removed by erosion. This need only be referred to here, as the whole subject has been thoroughly treated by Dr. Knowlton in his two papers on the stratigraphic position of the Lance formation.[1] It is necessary to state here only that the writer is in perfect agreement with Dr. Knowlton[2] as to the position of this unconformity and its being the place at which to draw the line between the Cretaceous and Tertiary, and further, to reiterate that the Judith River formation is the direct equivalent of the Lance formation, not only from its paleontological contents, as will be shown later, but also from its stratigraphic position as shown in the section given above.

[1] *Proc. Wash. Acad. Sci.*, XI (1909), 179–238; *Jour. Geol.*, XIX, No. 4 (May-June, 1911), pp. 358–76.

[2] *Jour. Geol.*, XIX, No. 4 (May-June, 1911), p. 376.

SOME TRIASSIC FOSSILS FROM SOUTHEASTERN ALASKA[1]

WALLACE W. ATWOOD

On the north shore of Hamilton Bay, a small re-entrant on the northwest coast of Kupreanof Island, there are rock exposures which have yielded certain Triassic fossils that may prove to be of special value in paleontologic studies.

From reports prepared by F. E. and C. W. Wright, Spencer Brooks, Kindle, and some others, it is evident that the more wide-spread geologic formations of southeastern Alaska outcrop in roughly parallel north-south belts; that the formations consist, in part of igneous rocks, in part of sedimentary rocks, and in part of metamorphic rocks; that most of the formations have suffered from intense deformation; that numerous intrusions of igneous rocks have occurred; and that the structural relations are exceedingly complex.

The formations included in this complex of older rocks vary in age from early Paleozoic to Triassic. They border and nearly surround the Tertiary coal basins that have thus far been located in this portion of Alaska. Detailed description of these formations as they appear at various localities may be found in the reports of the Alaskan Division of the United States Geological Survey, referred to above.

At Hamilton Bay the older rocks include some of Paleozoic age and some that are of Triassic age. They include limestones, argillites, limestone conglomerates, shales, and sandstones. Associated with these beds there is considerable basalt of a much younger age. The sedimentary beds are highly inclined and are a portion of a closely folded series of strata. They outcrop on the north shore of Hamilton Bay, and there form the northern limit of the area underlain by the Tertiary coal-bearing series.

[1] Published by permission of the Director of the United States Geological Survey.

The limestone conglomerate in the midst of this series, outcropping at the North, near the entrance to Hamilton Bay, is a peculiar formation in that there are huge angular blocks of limestone in it associated with bowlders ranging from one to three feet in diameter. The conglomerate formation is at least 100 feet thick, and may represent an important structural division line in the Mesozoic section.

The fossil collections secured from these older formations have been examined and reported upon by Dr. T. W. Stanton, as follows:

Collection No. 4819—North side of Hamilton Bay.
Pseudomonotis subcircularis (Gabb).
Horizon, Triassic.

Collection No. 4820—Hamilton Bay, North side, a few feet below No. 4819.
Pseudomonotis subcircularis (Gabb).
Numerous immature examples of this species.
Horizon, Triassic.

Collection No. 4821—North side of Hamilton Bay from bowlder in limestone conglomerate.
Rhynchonella. 2 or 3 species.
Spiriferina? sp.

The Rhynchonellas are of Mesozoic type, but the species listed as "*Spiriferina?*" may be a Spirifer, as punctuate structure has not been detected in it.

Collection No. 4822—From another bowlder in conglomerate at same place as No. 4821.
Rhynchonella sp. same as No. 4821.
Pecten sp.
Pleuromya? sp.
Several other undetermined pelecypods.
Trachyceras? sp.
Another undetermined ammonite genus.

This lot, like No. 4821 from the same conglomerate, seems to be of Triassic age. This determination is based on the character of two fragments of ammonite in No. 4822, the character of the Rhynchonellas of which one species is identical in both lots, and the absence of characteristic Paleozoic types.

According to Mr. Atwood's determination, this conglomerate is stratigraphically between the horizons of lots 4819 and 4823,

both of which are definitely determined to be Triassic. This would suggest that Nos. 4821 and 4822 may have come from concretions rather than bowlders, and that the conglomerate has no very great geological significance.

Collection No. 4823—North side of Hamilton Bay.
Halobia superba Mojsisovics?
Ceratites? sp.
Horizon, Triassic.

The pre-Tertiary formations appear to extend northward and northeastward through Kupreanof Island, but no further field-work was done in this locality on the older formations by the present writer.

PRELIMINARY NOTES ON SOME IGNEOUS ROCKS OF JAPAN. VI[1]

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VI. QUARTZ-SYENITE AND COMENDITE FROM THE OKI ISLANDS

Introduction.—Our geological knowledge of the Oki Islands is derived in the first place from the late Dr. T. Harada,[2] Mr. B. Minari,[3] and others, and subsequently from the more detailed work of Mr. M. Yamakami.[4] The last author's report and geological map were published in 1896 by the Imperial Geological Survey of Japan, and many rock-specimens collected by him are preserved in the Survey collection. Among them, I have found some interesting alkalic varieties, many of which have not yet been described in Japan; and their occurrence in our country, especially near the coast of the sea of Japan, is very interesting from a petrological point of view. In the summer of 1911, I had an opportunity to visit the islands and to make a collection of several varieties of these interesting rocks. The following description is a preliminary account of the petrological observations made on my journey, and of the quartz-syenite and comendite, the most interesting rocks that I collected.

For the chemical analyses of these rocks, made in the laboratory of the Imperial Geological Survey of Japan, I am greatly indebted to Mr. K. Yokoyama, and my sincere thanks are due to Professor B. Koto, for advice and assistance in the study of the rocks.

[1] Published by permission of the Director of the Imperial Geological Survey of Japan.

[2] T. Harada, *Versuch einer geotectonischen Gliederung der japanischen Inseln*, Imp. Geol. Survey, Japan, 1888; T. Harada, *Die japanischen Inseln*, Imp. Geol. Survey, Japan, 1890.

[3] B. Minari, Explanatory Text to the Agronomic Map of Izumo, Iwami, and Oki Provinces (in Japanese), Imp. Geol. Survey, Japan, 1895.

[4] M. Yamakami, Explanatory Text to the Special Geological Map of the Section Oki (in Japanese), Imp. Geol. Survey, Japan, 1896.

Morphological sketch of the Oki Islands.—The Oki Islands, lying within 132° 56′–133° 22′ E. long. and 35° 56′–36° 20′ N. lat., are off the coast of Izumo, the northwestern province of Honshû, at a distance of about 65 kilometers. There are four main islands, in two groups. One large island called Dōgo is situated to the northwest, and is separated by a strait 12 kilometers wide from the other three smaller ones—Chiburi-shima, Nishino-shima, and Nakano-shima, together known as Dōzen. There are also 180 islets and rocks included under the name of the Oki Islands. The total land-area is about 351 square kilometers.

The coast line of Dōgo is rather regular, and its shape is roughly circular, indented by the bay of Saigō on the southeast and by the bay of Fuku-ura on the northwest. Many other smaller narrow inlets occur mostly on the southern coast. The coast line of Dōzen, however, is irregular and is detached into three islands by narrow channels called Ōguchi, Akanadaseto, and Nakaiguchi. These islands are arranged in a triangular position on the arc of a circle.

Dōgo has a length of about 21 kilometers from south to north and a little shorter breadth from east to west. Its area is about 245.6 square kilometers, and the coast, in great part, ends abruptly against the sea, with elevations varying from 30 meters to 100 meters. The island is mountainous and morphologically divisible into two parts, the western and eastern districts (Fig. 1), separated by a watershed trending nearly north and south through the middle of the island. The western region consists of gently sloping ridges (Fig. 1), composed of rhyolite flows, averaging 300 meters in altitude. These flows have been eroded to deep and narrow valleys diverging toward the west and southwest from two isolated peaks, called Ōmine (666 m.) and Yoko-o-yama (568 m.), which are situated on the watershed. It is evident that the region was formerly covered by almost horizontal rhyolite flows. The eastern district is characterized by ragged peaks and isolated knolls, composed of several kinds of rocks. The highest point on the conical mountain of trachydolerites, named Daimanji (Fig. 1), is 646 meters in altitude. The south and east ridges descend gradually, but the mountains to the north and west have precipitous slopes and are very irregular.

The most striking physical feature of Dōzen is the circular arrangement of the three main islands. The largest island, Nishino-shima (55.23 sq. km.), lies on the northwest of the group; the smaller one, Nakano-shima (35.20 sq. km.), on the east; and the smallest, Chiburi-shima (14.82 sq. km.), on the south. An inland sea with an area of about 51.24 square kilometers is inclosed by the three islands. The most prominent peak, called Takuhi-yama (Fig. 2), 525 meters in height, is situated south of the middle part of Nishino-shima. The sea coast facing the ocean ends abruptly, as is the case at Dōgo, and the slope of the islands is steeper toward the inner side than toward the outer. Dr. T. Harada compared the form of Dōzen with that of Santorin in the Mediterranean.

Fig. 1.—Dōgo as seen from the south

Geological sketch of the Oki Islands.—In order to give a general idea of the structure of the Oki Islands, their geological features will be described briefly. The geological formations of the islands, in the order of their age from younger to older, are as follows:

1. Alluvium.
2. Trachydolerites and basalts.
3. Diluvium (?).
4. Trachytes.
5. Trachyandesites and trachydolerites.
6. Trachytic rhyolites.
7. Greenish trachyandesites.
8. Soda-rhyolites.
9. Schistose granites and quartz-syenites.
10. Andesites.
11. Tertiary strata.

The islands consist mainly of volcanic rocks, which were erupted at several times, probably from the middle of the Tertiary

to the beginning of the Diluvium. Besides these extrusive rocks, there are intruded masses of granites, quartz-syenites and their allied porphyries, occurring in a limited area. It is highly probable that all these igneous rocks are younger than the bottom beds of the Tertiary, which make up the base of the islands.

At Dōgo, the Tertiary formation is met with in the southwestern and northeastern sea-cliffs overlaid by lava flows, and in the middle of the island, where the elevation is about 300 meters above the sea-level. It consists of tuffs, conglomerates, sandstones, and shales, in which deposit plant fossils are preserved. The formation is intruded by andesite sills and by schistose granites and their allied porphyries. It is folded and faulted, and its strikes and dips are variable in places, but the general dip is gentle.

At Dōzen, the Tertiary formation occurs in a small area and is free from andesite sills, so far as the writer's observation goes. But it is intruded by quartz-syenite and its apophyses, and at the place of contact, metamorphosed sandstone with abundant brown mica is exposed.

The age of the formation is considered to be Miocene, corresponding to that of the formation along the northwestern coast of Honshū.

The Diluvium is exposed near Tōgō, a small village in Dōgo. It consists of gravels and blocks of trachydolerites and trachytic rhyolites, and is overlaid by the younger trachydolerite flow. The outcrop is clearly seen at a new cutting, a little south of Tōgō. The formation seems to have been locally deposited in a lake, which now forms the bay of Saigō.

The Alluvium is river deposit, seen in a limited area along valleys. The description of

Fig. 2.—Dōzen as seen from the southeast

the geological relations of the igneous rocks[1] will be given with the petrographical notes of each kind of rock. However, some striking geological features may be mentioned. Enormous quantities of trachydolerites and trachyandesites were erupted near the end of the igneous activity in the region, and Dōzen was mainly composed of these rocks. Their eruptions seem to have occurred at several localities. After some interval of time there was a depression of the middle of the land which formed the inland sea already described. This movement fractured the ground greatly and gave rise to the eruption of trachytes. The rocks occur as flows and dikes; the flows form most prominently Takuhi-yama, and the dikes occur in very remarkable radial arrangement having Takuhi-yama as an approximate center, traversing trachydolerites, trachyandesites, and the Tertiary formation; but no dike was seen cutting the syenite mass. The occurrence of these dikes is analogous to that of the basic dikes in Rum, Scotland, described by Harker[2] and to that of the basaltic and trachytic dikes in the Highwood mountain, Montana, described by Pirsson;[3] though the petrographical character of the rocks and the number of the dikes are not the same.

QUARTZ-SYENITE

Field observation.—The rock is found in a small mass, only, at the northeastern foot of Takuhi-yama at Dōzen. It occurs intruded in the Tertiary formation and is covered by glassy trachytes which build up Takuhi-yama. Its contact action on the Tertiary rocks is clearly seen, and the metamorphosed shaly sandstone is permeated by a brown mica as a contact mineral. The endomorphic effect is not so pronounced as that observed in other countries where this rock type has been described by several authors. The texture becomes gradually fine-grained and inconspicuously porphyritic by the development of feldspar 1 cm. in average length. Hornblende, which occurs as an essential mineral in the main mass,

[1] The petrographical notes on several kinds of rocks from the islands are not described in this paper. They will be published in the report of the Imperial Geological Survey of Japan.

[2] Harker, *Memoirs of the Geological Survey, Scotland*, 1908, p. 143.

[3] Pirsson, *Bulletin No. 237, U.S. Geol. Surv.*, 1905, p. 20.

is almost entirely replaced by biotite in the fine-grained part. If the Tertiary formation, through which the syenite intrudes, proves to be Miocene as considered now, the syenite will be probably the youngest rock of this kind which has ever been described.

Megascopic character.—It is medium-grained, evenly granular, and almost compact, though miarolitic cavities are present. On a freshly fractured surface, the color is light gray with somewhat waxy luster. The rock consists mainly of feldspar, which is light gray, due to clouded, minute inclusions; and, in some crystals, a faint blue shiller is recognizable. Close examination shows certain feldspars developed with a more or less idiomorphic and thick tabular habit. Black hornblende occurs in moderate quantity, scattered through the feldspathic mass. Its form is irregular, but the general shape is prismoid with an average length of 3 mm. Biotite is quite subordinate in amount, and quartz is scarcely detected with a lens.

Microscopical character.—The constituent minerals present in the rock specimen used for a chemical analysis are quartz, alkali feldspar, plagioclase, hornblende, biotite, diopside, olivine, apatite, zircon, ilmenite, and magnetite; besides zeolites in miarolitic cavities. The amounts of diopside and olivine are variable even in specimens taken from very near one another. A thin section shows the presence of allanite. The rock consists essentially of feldspar with hornblende; and the other minerals, with the exception of allanite, are also constant ingredients, though their quantities are subordinate and variable. The texture, for the most part, is granitoid, but there are some peculiarities of micrographic intergrowth of feldspar and quartz and of miarolitic cavities.

The feldspars are mostly alkalic (orthoclase, microperthite, and cryptoperthite), but plagioclase is not rare. The latter mineral is represented by oligoclase and albite, which, besides perthite, is also found as the border of the alkali feldspar. The alkali feldspars are tabular, parallel to (010), and are variable in shape, some of them being irregularly contoured and others rather euhedral. They are clouded with dusty particles and frequently show the zonal structure due to chemical differences. The outer shell is usually thin and clear, in strong contrast to the clouded inner part. The former

show slightly higher refraction and birefringence than the latter. The extinction angle of the shell is $+10°$ on a section nearly parallel to (010), while the inner part shows $+7°$ on the same section. From these characters, the outer material must be referred to a variety of anorthoclase with especially high content of soda. Inclusions are plagioclase, sharply defined apatite, a few crystals of zircon, magnetite, and quartz. The last mineral appears micrographically intergrown in the peripheral part of the feldspar. No microcline structure is observed. The oligoclases usually occur in prismatic form and are, in many instances, included in the alkali feldspar. They show distinct polysynthetic lamellae and are clearer, owing to fewer inclusions, than those in the alkali feldspar. They vary in composition within a limited range, judging from their indices of refraction. Generally the refractions are slightly higher than those of quartz and Canada balsam and the maximum symmetrical extinction angle of a calcic variety exceeds $17°$.

The hornblende is mostly greenish-brown, associated with a bluish-green variety. Its form is irregular in general; sometimes more or less idiomorphic in elongated or short prismatic form. Cross-sections exhibit the characteristic cleavage and rhombic outline, or sometimes six-sided section elongated along the axis b, having the first pinacoid strongly developed and with the unit prism subordinate. The bluish-green variety occurs as fringes or borders, and as inclusions in the brown, and as an individual of quite irregular shape in very rare instances. In the first instance the green variety does not entirely inclose the brown, and in many instances it occurs on the terminal faces of the brown crystal. These two varieties exhibit almost no differences in optical orientation. They are strongly pleochroic: X, light yellow; Y, dark brownish-yellow; Z, greenish-brown to olive-green; absorption $Y>Z>X$, on the greenish-brown variety, and X, light yellow; Y, yellowish-green; Z, bluish-green; absorption $Z>Y>X$, on the bluish-green variety. They extinguish in nearly the same position and the angle between Z and c on (010) is from $26°$ to $28°$ in the obtuse angle B. From these properties, the hornblende seems to be barkevikite near katophorite or hastingsite, but it is not like it in the larger optical angle (?) and the higher birefringence.

Quartz is present in small amount as shown by the chemical analysis, but it is sufficient to characterize the rock as quartz-bearing syenite. It occurs interstitially, or intergrown micrographically, with the alkali feldspar, and frequently as an infiltration in miarolitic cavities with zeolite. In the last case, it often shows distinct euhedral outline.

Biotite is sparingly present, and usually occurs associated with hornblende. It is optically negative, and the plane of the optic axes lies in the plane of symmetry. The optical angle measured is $2E=36° 23'$. The pleochroism is strong: X, brownish-yellow; Y, brown with violet tinge; Z, dark reddish-brown; and absorption, $Z>Y>X$. Magnetite and apatite are included in it.

The diopside shows an irregular form and is colorless or pale violet, being slightly pleochroic. Its quantity is variable and it shows a tendency to replace hornblende. Olivine occurs in more or less automorphic outline, and is quite fresh. It is almost free from inclusions with the exception of a few minute crystals of magnetite and apatite. The ilmenite and magnetite are present in association with each other. The former is in irregular form and is characterized by the decomposed product, leucoxene. Apatite occurs conspicuously in elongated prismatic form. It is comparatively abundant.

The mineral described here as allanite is not exactly determinable, owing to its rare occurrence and deep color, in some instances being almost opaque. It is strongly pleochroic from deep reddish-brown to opaque. In some respects, it resembles aenigmatite or rhönite. Its form is long prismatic with irregular terminations. Zonal structure is not recognizable, and cleavage is also indeterminable. One section observed is cut nearly perpendicular to an optic axis, its cross-bar appearing in the middle of the field. The case is very similar to that of the allanite-like mineral in the Mt. Belknap syenite, described by Pirsson and Washington. The characters of the mineral will be determined after further examination of more thin sections.

Chemical character.—The analysis of the rock, collected from the eastern foot of Takuhi-yama, Ezirigasaki, Kuroki-mura, Dōzen, was made by K. Yokoyama in the laboratory of the Survey. It is given

in column A in the following table. Compared with foreign rocks, the rock from Oki has a close resemblance to the akerite-porphyry, described by Brögger;[1] the augite-syenite, described by Cushing;[2] the quartz-syenite, described by Pirsson;[3] and the syenite, described by Pirsson and Washington.[4] It differs from the pulaskite from Fourche Mountain, described by Williams[5] and by Washington[6] respectively, in having less alumina, less alkalies, and more iron oxides. These relationships are shown in the following table:

	A	B	C	D	E	F	G
SiO_2	61.83	62.60	63.45	65.54	60.75	60.25	60.03
Al_2O_3	17.08	18.07	18.31	17.82	19.68	20.40	20.76
Fe_2O_3	2.14	2.28	0.42	0.74	1.54	1.74	4.01
FeO	2.71	2.25	3.56	1.15	2.98	1.88	0.75
MgO	0.89	1.16	0.35	0.98	0.81	1.04	0.80
CaO	2.24	2.27	2.93	1.92	2.29	2.00	2.62
Na_2O	4.93	5.45	5.06	5.55	4.89	6.30	5.96
K_2O	5.37	5.22	5.15	5.58	5.90	6.07	5.48
H_2O+	1.60*	0.50	0.30	0.54	0.08	0.23	0.53
H_2O-	....	....	....	....	0.24	0.10	0.06
TiO_2	0.30	....	0.07	0.11	0.63	0.14	....
ZrO_2	....	....	....	....	....	trace	....
P_2O_5	0.35	....	trace	....	trace	0.15	0.07
SO_3	....	....	....	....	....	0.13	....
MnO	0.12	....	none	trace	trace	trace	trace
BaO	....	....	0.13	....	....	....	....
Li_2O	....	....	....	trace	....	....	....
Total	99.56	99.84	99.73	99.92	99.79	100.47	101.07

* Loss on ignition.

A. Quartz-syenite from the eastern foot of Takuhi-yama, Dōzen, Oki. K. Yokoyama, analyst.

B. Åkerite-porphyry from Ullernas, Norway. G. Forsberg, analyst.

C. Augite-syenite from Loon Lake, Franklin County, N.Y. E. W. Morley, analyst.

D. Quartz-syenite from Highwood Peak, Highwood Mountain, Mont. Pirsson and Michell, analysts.

E. Syenite from the western slope of Mt. Belknap, N.H. H. S. Washington, analyst.

F. Pulaskite from Fourche Mountain, near Little Mountain, Ark. H. S. Washington, analyst.

G. Pulaskite from Fourche Mountain, near Little Mountain, Ark. R. N. Brackett, analyst.

[1] Brögger, *Zeitschrift für Krystallographie*, XVI (1890), 49.

[2] Cushing, *Bulletin of the Geol. Society of America*, X (1899), 183.

[3] Pirsson, *Bulletin No. 237, U.S. Geol. Surv.*, 1905, p. 63.

[4] Pirsson and Washington, *American Journal of Science*, XXII (1906), 446.

[5] Williams, *Ann. Rep. of the Geol. Surv., Arkansas*, II (1890), 70.

[6] Washington, *Journal of Geology*, IX (1899), 1901.

Norms, calculated from the analyses, are as follows:

	A	B	C	D	E	F	G
Quartz	6.1	3.2	5.2	6.1	2.0	....	....
Orthoclase	31.7	31.1	31.1	32.8	35.0	36.1	32.8
Albite	41.9	46.6	42.4	47.2	41.4	41.0	45.6
Anorthite	8.6	8.9	11.7	7.2	11.4	9.2	13.3
Corundum	....	....	....	....	1.0	....	....
Nepheline	....	....	....	....	....	6.2	2.6
Diopside	....	2.1	2.2	1.9	....	0.8	....
Hypersthene	5.8	4.2	6.0	3.1	5.3	....	....
Olivine	....	....	....	....	....	3.1	1.4
Magnetite	3.0	3.2	0.7	1.2	2.1	2.6	2.6
Hematite	....	....	....	....	....	....	3.2
Ilmenite	0.6	....	....	....	1.2	0.3	....
Apatite	1.0	....	....	....	....	....	....

The ratios of the rock from Oki are as follows:

$\frac{\text{Sal}}{\text{Fem}}$ 8.49

$\frac{\text{Q}}{\text{F}}$ 0.07

$\frac{K_2O'+Na_2O'}{CaO'}$ 4.42

$\frac{K_2O'}{Na_2O'}$ 0.71

By the Quantitative System, the rock may be classified as pulaskose, near lauvikose.

As will be seen from the above description, the present rock is chemically close to acidic åkerite, that is, pyroxene-syenite, but it has mineralogically and chemically a close relation to the syenite from Belknap Mountain, New Hampshire. The petrographical characters of the rock show also some relation to normarkite on the one hand and to umptekite on the other. So it is concluded that the Oki rock is characterized, by mineralogical and chemical properties intermediate with respect to nordmarkite, umptekite and åkerite, though it is nearer to the last type.

THE EFFECT OF IGNEOUS INTRUSIONS ON THE ACCUMULATION OF OIL IN NORTH-EASTERN MEXICO

V. R. GARFIAS
Los Angeles, Cal.

The region where the occurrences herein noted were observed comprises the portion of the Mexican coastal plain between the Panuco and Tuxpan rivers in the northern part of the state of Vera Cruz.

The formations involved in the geology of this area are of Cretaceous and Tertiary age, with unimportant Quaternary deposits near the coast. For convenience, they will be separated according to lithology into three divisions; the lower of which is made up of several thousand feet of limestones overlain by a series of alternating limestones and shales, the whole of Cretaceous age; the middle, of uniform shales and marls with a total thickness of about 3,000 feet, of upper Cretaceous-Eocene age; and the upper, of Tertiary sands, clays, limestones, and conglomerates, having an aggregate thickness of about 700 feet.

The marked characteristic of the geology of this region is the large number and magnitude of the volcanic intrusions, the remnants of which are represented in places by isolated basaltic cones, breaking the monotony of the coastal plain. The volcanic activity is more pronounced in the southern portion of the area, attaining its greatest development in the Otontepec range, an irregular basaltic mass about 2,000 feet high. The location of many of the intrusions was probably controlled by well-defined fault lines, and cross-faulting or any decided weakness of the underlying basement may also have played an important part in their distribution. The intrusions occurred during late Tertiary or possibly early Quaternary times, and consist of basalt accompanied in places by volcanic ash and conglomerate. Most of the surface indications of oil are closely associated with the basalts and hundreds of such

phenomena occur throughout the area examined. Among the localities where oil seepages are abundant might be mentioned La Pez, La Dicha, Chijol, and Santa Margarita, near the Eban field; San Geronimo, La Merced, Rancho Abajo, Monte Alto, and Los Higueros, between the famous Dos Bocas and Casiano; Casiano, Cervantes, Tres Hermanos, Tinaja, Ojo de Brea, Chapopotillo, Monte Grande, Moralillo, Cerro Azul, Juan Felipe, Las Borrachas, Piedra Labrada, and Cerro Viejo, between the producing fields of Casiano and Potrero del Llano.

The intimate association of the volcanic intrusions and some of the producing fields is so apparent as to be unquestionable, and the problems in this connection relate chiefly to the effect of the basalt on the structure and texture of the intruded beds which resulted in their becoming capable of storing large amounts of oil under tremendous gas pressure.

The general conception of the form of these intrusions is that of a more or less irregular cone, in a normal position, the vertex of which may or may not reach the surface. Were these conditions fulfilled in the Mexican coastal plain, a well drilled near an outcrop of basalt would eventually strike the side of the cone and thus preclude further progress. This assumption is certainly not corroborated by actual experience in the fields, as many of the best producers are located in very close proximity to intrusions, and in some cases the basalt has been penetrated for several feet and the well continued to the oil reservoirs below.

In order to account for these discrepancies the writer performed a rather crude experiment, as a result of which were obtained some interesting data which seem to throw considerable light on the behavior of the intrusions and their effect on the intruded beds. Assuming the thickness of the uniform Cretaceous-Eocene shales as 3,000 feet, and that of the average intrusion as 1,000 feet, it was thought that the effect of the latter as it penetrated through the uniform series of shales would in some ways be parallel to that of a nail driven through an unbound book of a thickness three times as great as the diameter of the nail. The experiment was tried while the book was resting, first on a board, then on a folded blanket, and again on the open end of an inch pipe, and the

results obtained were remarkably uniform. It was found that the leaves first penetrated were distorted only within a comparatively small radius, and that the zone of distortion increased toward the bottom in a more or less uniform ratio. A horizontal plan showed that in order to take care of the buckling near the nail, the first leaves had been torn at right angles and that the number of fissures naturally decreased as the zone of bending increased. It was also noticed that the fracturing and folding of any leaf around and near the nail was to a great extent controlled by the location and nature of displacement in the leaves immediately under, and this resulted in the formation of zones of dislocation along approximately vertical planes, most of which were closed before reaching the surface owing to the lesser number of fractures in the leaves last penetrated.

From these experimental observations and the results of actual experience in the developed portions of the fields, the following tentative conclusions have been drawn:

The thickness of the basalt intrusions as they pass through the Cretaceous-Eocene shales toward the surface increases roughly in a uniform ratio.

The horizontal zone of folding of the shales around the intrusions increases toward the surface.

The horizontal zone of fracturing varies with that of folding, but the number of fractures is greater in the deeper beds.

The fractures seem to occur along roughly vertical planes, thus forming deep well-like channels.

These vertical holes, partially filled with basalt and shale, could be effectively capped before reaching the surface, owing to the fewer number of fractures in the higher beds and the increasing cross-section of the intrusion toward the surface.

Before discussing the relation of the intrusions to the accumulation of the oil and gas, it is thought advisable to summarize certain views regarding the origin of the oil in this region:

For obvious reasons, the oil did not originate in the 700 feet of sandy limestones, conglomerates, and clays of Tertiary age, the remains of which are now exposed in patches here and there.

If the 3,000 feet of Cretaceous-Eocene shales were the source of the oil, they would show a more or less bituminous character

throughout, or at least be of such an organic nature as to account for their furnishing the great quantities of oil in these fields. The shales which are exposed over nearly the whole area, however,

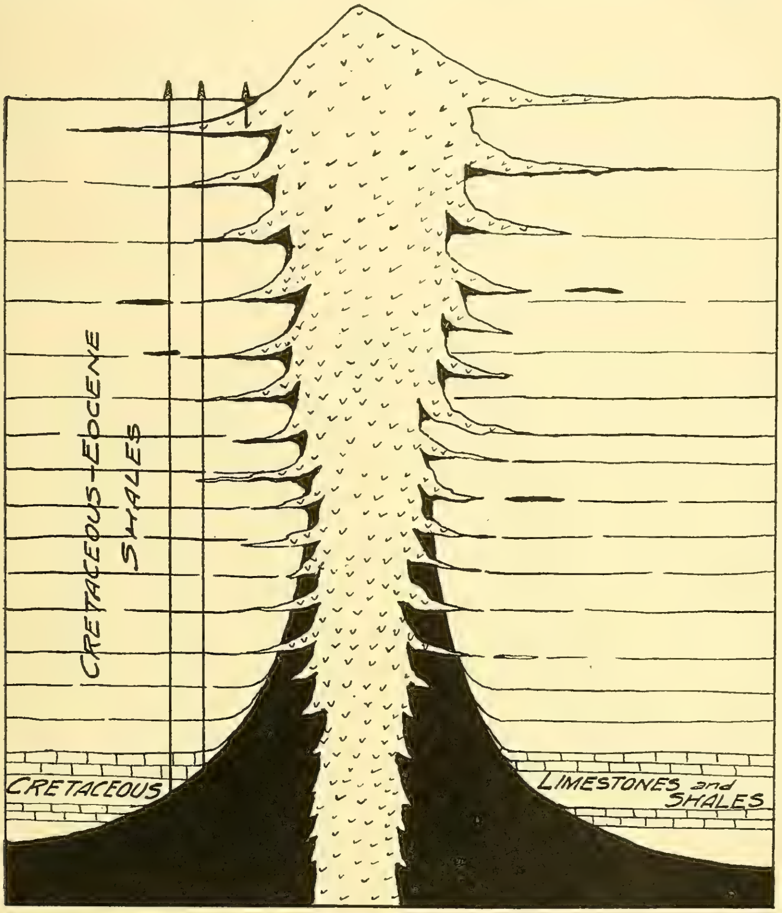

FIG. 1.—Hypothetical section showing basalt intrusion reaching the surface and resultant conditions in the intruded beds, conducive to the accumulation of oil. The two deep wells tapped the oil zone after penetrating the basalt, while the well nearest to the cone was abandoned in the basalt.

show signs of oil only near intrusions, and in all the exposures examined were of a uniform inorganic nature.

The migration of oil in impervious shales of this nature takes

place mainly along bedding planes, and any barrier, such as the basalt intrusions, cutting across the planes of migration, will effectively intercept the flow. If resultant conditions are favorable, the vicinity of the barrier will become an ideal zone of concentra-

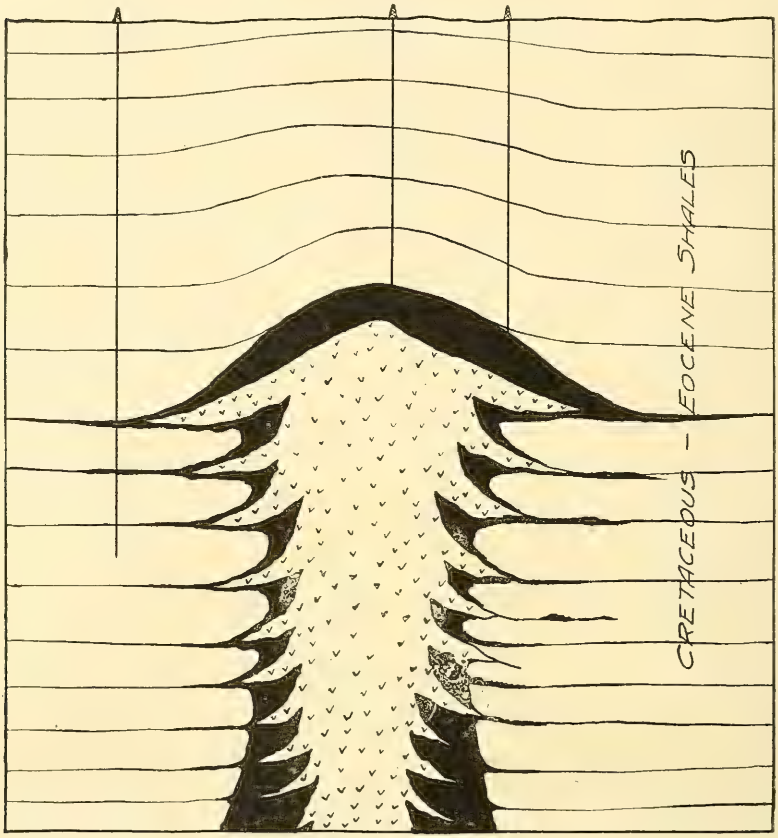

FIG. 2.—Hypothetical section of a basalt intrusion penetrating the Cretaceous-Eocene shales to a point below the surface, illustrating how a deep well might encounter only "showings" of oil, and two neighboring shallower wells obtain a fair production in the shales.

tion for the flow of all the lateral channels penetrated, and, owing to the large drainage area contributing to the accumulation, this will be comparatively large, even if the amount of organic matter in the shales is small. In other words, the basalts which intrude

the Cretaceous-Eocene shales certainly afford one of the most effective means to concentrate whatever hydrocarbons might have been disseminated throughout these beds.

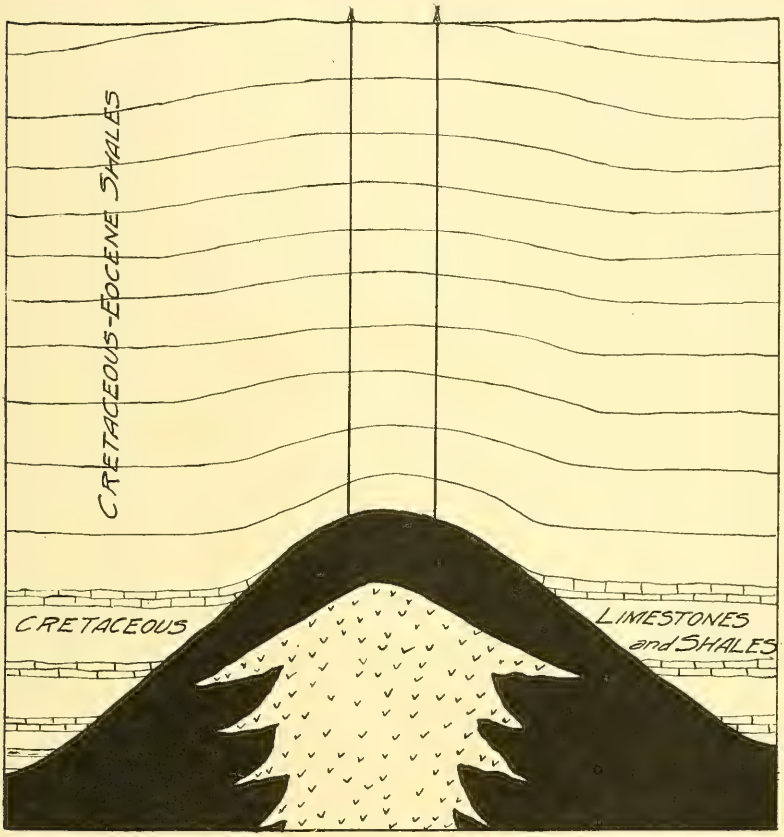

FIG. 3.—Hypothetical section of basalt intrusion penetrating the series of Cretaceous limestones and shales without disturbing the Cretaceous-Eocene shales, and giving rise to a dome of fractured and porous material, effectively covered with an impervious cap-rock. The large production of some of the Mexican gushers can readily be accounted for on this hypothesis.

Finally, it is apparent that if the Cretaceous limestones yielded the oil, it must have been before the event which changed them to their present compact and rather crystalline nature, and it is probable that such a condensation of the oil was coincident with

the change in the nature of the beds. The oil could then have migrated along fissures toward the upper beds, aided by the action of water, and collected in the upper Cretaceous limestones and shales, to be concentrated in the favorable zones created by the igneous intrusions. Such migration had necessarily to take place after the deposition of the Cretaceous-Eocene cap-rock.

The accompanying figures summarize graphically the writer's conception of the effects of the igneous intrusions on the accumulation of oil in northeastern Mexico. Fig. 1 shows an intrusion which reaches the surface. In this case some oil may percolate through the shales, forming seepages near the basalt outcrop, and wells of varying productiveness may be located at comparatively short distances from the outcrop. If the intrusions penetrated the Cretaceous-Eocene shales to a point below the surface (Fig. 2), these would be arched above the basalt, thus affording a dome-shaped reservoir in the shales, which might prove commercially productive for a comparatively short time. If, however, the intrusions perforated only a portion of the series of limestones and shales at the top of the Cretaceous limestones (Fig. 3), the resultant dome of porous and fractured material, capped by a thick cover of impervious shales, would form an ideal reservoir, which, if tapped, would readily account for the tremendous gushers characteristic of this region. Any and all of these conditions may exist, and it is probable that, with certain modifications, all do occur at one point or another in the portion of the Mexican coastal plain herein mentioned.

August 5, 1912

EDITORIAL

THE WILLIAMS PHOTOGRAPHIC PROCESS

It gives us pleasure to publish the following letter of Roger H. Williams announcing the dedication to the free use of scientists of the Williams patented process for preparing fossils and other objects for photographing. Paleontologists in particular will appreciate this generous action and will be deeply gratified that the original wish of the inventor of the process, Dr. Henry S. Williams, and the purpose of his son, the proprietor of the patent, are thus consummated. This is but one of many valued contributions to paleontolgy and geology by Dr. Williams which have placed his colleagues under obligations and have won their high esteem.

T. C. C.

September 12, 1912

Editor of "Journal of Geology":

DEAR SIR: It may be of interest to your readers to know that as of July 1, 1912, there has been dedicated to the free use of science and scientists the patented process for photographic illustrations (U.S. Pat. No. 640,060), owned by the undersigned and known among paleontologists, who found it especially useful in specimen work, as the "Williams Process."

In brief, it consists in the deposition by sublimation on the object to be photographed of an extremely tenuous monochrome film for the purpose of obviating the reflection, refraction, and distorted shadow values common in ordinary photography of certain classes of objects.

It has been a matter of great regret to the writer that a long-continued and expensive investigation, arising out of an entirely legitimate difference as to the scope and validity of the patent, has delayed until now the fulfilment of the original intention of the writer to make this dedication so soon as the expenses incurred in perfecting and establishing the patent should have been secured by the moderate royalties hitherto charged. The outcome of the controversy has entirely justified the writer's position—the opinion of the opposing experts conclusively confirming the fundamental character of the invention.

As one interested in science, the writer would have been pleased if his means had permitted the assumption of all the expenses of this patent without thought

of recoupment, and is heartily sorry that there are those who felt that the failure to do so is culpable. If it is so, I can only plead that it is so in violation of no code with which I am familiar.

In view of the fact that the invention was originally made by my honored father, Dr. Henry Shaler Williams, of Cornell University, it is most desirable that certain facts be stated for the benefit of those who may in the past have been under a misapprehension as to his relation to the patent. Almost immediately after being granted, the patent was transferred from him to me in good faith and in consideration of the assumption of debts incurred in its development. My father's wish always has been that the process should be made freely available to science gratis, and I promised him it should be as soon as its financial situation could be cleared up. It has never yielded a cent of profit to Henry Shaler Williams, nor was it taken over or ever handled with the idea of exploiting science or making commerce of its needs. This cannot be stated too strongly. With the long-drawn-out controversy referred to my father has not only had nothing to do, but has repeatedly endeavored to induce me to abandon it.

Therefore the blame in the matter, if blame there be, is entirely mine and I cheerfully shoulder it; but he should be given complete exoneration from any such charge. Those who have been disposed to think critically of Dr. Williams in connection with the patent have been doing a great and unwarranted injustice to a high-principled man, whose character and whose long and disinterested devotion to science should have made it unnecessary to break the silence he has long maintained, as I now do, without his knowledge, to right a wrong; and, as I sincerely hope, to remove completely any ground for misgiving on the part of any one of his many distinguished friends toward a loyal and worthy colleague.

Roger H. Williams

REVIEWS

Geology and Mineral Resources of Parts of the Alaska Peninsula. By WALLACE W. ATWOOD. Bull. U.S. Geol. Surv. No. 467.

All available material bearing upon the geology and mineral resources of the Alaska Peninsula have been compiled and presented in this bulletin, and a considerable body of new material secured during the season of 1908 by Wallace W. Atwood and H. M. Eakin while investigating the coal fields of the Alaska Peninsula is here presented for the first time.

A large general map of the general geology of the peninsula and special detail maps of the Herendeen Bay and Unga Island region, and of the Chignik Bay region, are embodied in the report.

The geologic formations exposed in the peninsula range in age from Upper Triassic to the present. The Herendeen section, which has been worked in detail, includes representatives of the Upper Jurassic, Lower and Upper Cretaceous, Eocene, Miocene, Pleistocene, and Recent. Associated with the clastic sediments of this region there are some limestones and vast quantities of volcanic material, some of which appear to be of late Eocene age and some post-Miocene. There are active volcanoes in the region today adding to the pyroclastic rocks of the region.

The available coal measures in the Herendeen Bay region are in the Upper Cretaceous formation. A poor grade of coal or lignite is also found in rocks of Eocene age.

The Unga Island coal field located at Coal Harbor contains lignitic coal of Eocene age.

The Chignik Bay section includes rocks of upper Jurassic age, Upper Cretaceous, Eocene, and later volcanic, glacial, and post-glacial formations. The workable coal in the Chignik Bay field is also found in rocks of Cretaceous age.

Mr. Atwood has included a description of the general geographic and climatic conditions in the Alaska Peninsula, the present status of gold, copper, and coal mining, and a series of suggestions to the prospector.

The report is especially well illustrated with photographic views, numerous structure sections, and topographic sketches, and includes a somewhat full statement of the geomorphology of this portion of Alaska. The field work was carried on under difficult conditions and the report is a welcome addition to the available material on a little-known portion of the continent.

The Inland Lakes of Wisconsin. By EDWARD A. BIRGE and CHAUNCEY JUDAY. Bulletin XXII, Scientific Series No. 7, of the Wisconsin Geological and Natural History Survey.

This report deals with the dissolved gases of the water and their biological significance. Five years have been spent in this investigation. The work was first undertaken and outlined by Mr. Birge, who has kept general oversight over the work throughout the investigation and who has prepared the introduction to the present volume, but Mr. Juday has taken more and more of the responsibility of the investigation and is credited with the preparation of the body of the report.

As stated in the opening chapter, the primary object was to make a general survey of the lakes situated in various parts of Wisconsin in order to ascertain the status of the physical, chemical, and biological conditions which exist in them. Special consideration was given to lakes existing in different portions of the state and under different climatic conditions. The waters were examined for their content of oxygen, carbon dioxide, nitrogen, methane, carbon monoxide, and some other gases, and analyses were made of the mineral content.

The report gives a reasonably full account of the dissolved gases in the waters and sets forth the seasonal variations of these gases, their vertical distribution, the effect of the seasons and the plankton on the quantity and distribution of the gases, but the authors frankly admit that many of the biologic problems associated with their studies have not been solved.

The question why different lakes that are of about equal age, that have the same species of plankton, where temperatures do not differ widely, where the chemistry of the waters is not greatly different, where the planktons have had apparently the same advantages for development, differ so widely in productivity or ability to support a population of plankton, is not solved, and many other problems of a biological and chemical nature have arisen during the investigation which invite further study.

W. W. A.

Atlas photographique des formes du relief terrestre. Selected and prepared for publication by an international Commission appointed at the Ninth International Congress of Geography.

The plan of this atlas involves the preparation of nine volumes each to contain 48 plates, and each plate to be accompanied by a text descriptive of the geologic and physiographic features shown in the view. The

few sample plates which have been issued characterize the work as excellent. These volumes cannot but be of great interest and value to all members of the geologic and geographic professions and also to laymen.

The arrangement of the material in the nine volumes is as follows:

1. Relief features due to weathering and disintegration.
2. Simple features due to stream erosion.
3. Complex features due to stream erosion.
4. Land forms influenced by the nature and composition of rocks.
5. Features influenced by geologic structures.
6. Glaciers and relief features associated with ice action.
7. Relief features due to wind work.
8. Shore-line features.
9. Relief features due to vulcanism.

The Executive Committee of the commission consists of J. Brunhes, E. Chaix, and Emm. de Martonne. The American members of this commission are W. M. Davis and Wallace W. Atwood.

The price of each volume of the series has been placed at Fr. 30, and it is contemplated that 48 plates, the equivalent of one volume, will be issued each year.

W. W. A.

Illinois State Geological Survey. Bulletin No. 16. Urbana, 1910. Pp. 402; pls. 37; figs. 9.

This volume deals chiefly with the oil, coal, lead, and zinc resources of the state, and contains the following papers: "The Administrative Report for 1909," by Frank W. DeWolf, acting director, pp. 11–23; "Elizabeth Sheet of the Lead and Zinc District of Northern Illinois," by G. H. Cox, pp. 24–41; "Oil Resources of Illinois with Special Reference to the Area Outside the Southeastern Fields," by Raymond S. Blatchley, pp. 42–176; "Studies of Illinois Coal," a series of papers consisting of: An Introduction, by F. W. DeWolf, pp. 178–81; "The Illinois Coal Field," by A. Bement, pp. 182–202; "Chemical Composition of Illinois Coal," by S. W. Parr, pp. 203–43; "The Geology and Coal Resources of the West Frankfort Quadrangle," by G. H. Cady, pp. 244–65; "The Geology and Coal Resources of the Herrin Illinois Quadrangle," by T. E. Savage, pp. 266–85; "The Geology and Coal Resources of the Murphysboro Quadrangle," by E. Wesley Shaw, pp. 286–94; "Mine Rescue Work in Illinois," by R. Y. Williams, pp. 295–99; "Diamond Drill Core from Franklin County," Interpretation by Jon Udden, pp. 300–301. The volume contains also a paper on the

"Faunal Succession and the Correlation of the Pre-Devonian of Southern Illinois," by T. E. Savage, pp. 302–41, and a joint paper by Udden and Todd "Structural Materials in Illinois," pp. 342–90.

F. M. H.

Mineral Resources of the United States, 1909. Washington: U.S. Geological Survey, 1911. Part I, "Metals," pp. 617, plate 1; Part II, "Nonmetals," pp. 942.

The usual statistical tables are extended to include 1909. A general increase in production over that of 1908 is shown, but only a few products have recovered to the high values of 1907. Among these is aluminum, which showed in 1909 an increase of 206 per cent over 1908.

Compared witht the figures for production in 1908 only thirteen out of the seventy-four items listed show a decline. Of these platinum shows an increase in total value in spite of a 15 per cent decrease in production. Iron and copper show notable increase, both surpassing in quantity the output for 1907.

Among other changes the following points are of interest:

California shows an increase of 20 per cent in its petroleum output, partly due to the development of the Coalinga field. Colorado shows a general decline in its major products but a slight increase in total value.

Renewed activity in the Joplin district increased Missouri's zinc output by 4,000,000 lbs., bringing it almost up to the production in 1907.

The opening of great porphyry deposits in the Ely district brought Nevada into fifth rank among copper producers with an increase of 350 per cent over the previous year.

The shut-down of the Homestake mines decreased the gold output of South Dakota by more than $1,000,000.

As in 1908 California led in oil production with Oklahoma second. Illinois continued in third place in spite of a slight drop in output.

Conservationists will note with some satisfaction the continued increase in the use of retort ovens in the coke industry.

A. D. B.

High School Geography, Physical, Economic and Regional; Pts. I and II, Physical and Economic. By Charles R. Dryer. American Book Co., 1911. Pp. 340.

The author of this new high-school text is already well known for his elementary textbook of physiography published eleven years ago and for many valuable papers upon Indiana geography. The present work is an attempt to combine an outline of commercial geography

with what is commonly included under physical geography and to adapt the book to a high-school course extending over a half-year. A supplementary volume is to be added for the use of schools which can devote more time to the subject.

The keynote of the book is the dependence of human life upon natural conditions. In the second part, which is entitled "Economic Geography," we find an excellent preparation for a study of conservation, the importance of which is now beginning to be realized. This section follows logically and naturally the physical geography, its four chapters being devoted to: natural resources and food supply; clothing and construction materials; heat, light, and power; and manufacture, trade, and transportation.

The book has an unusual number of maps, both in contour and in color; and its other illustrations, while particularly well chosen, are poorly reproduced. Specially interesting are the cloud photographs and the series chosen to illustrate plant regions. Geographical divisions used in descriptions are natural rather than political, which is a decided advantage.

W. H. H.

Rocks and Their Origin. By G. A. J. COLE. Cambridge University Series, 1912. Pp. vi+175.

There is always a danger that because of the special interest of the unusual and bizarre, the common objects in Nature's storehouse will be neglected. In this little manual Professor Cole has invested limestones, sandstones, and shales with interest while teaching important facts which are quite likely to be overlooked. Though written in an attractive style, the book's appeal will be strongest to the serious student of geology, for it is surprising how much has been compressed within its pages. The latter third is devoted to the igneous rocks and metamorphic rocks and treats of broad problems of origin and differentiation. The book is thoroughly up to date and concludes with a very valuable series of references each referred to by a number in the text.

W. H. H.

The Mining Districts of the Western United States. By JAMES M. HILL. Bull. No. 507, U.S. Geological Survey. Washington, 1912. Pp. 309; pls. 16.

A catalogue of the mining districts in the western part of the United States, using as a basis the map compiled by Lindgren in 1907. The districts are arranged by states, with subdivisions by counties. An alphabetical list is found in the index. In each district the location,

type of deposit, and metals produced are noted and a short bibliography of U.S. and state geological survey publications relating to the region is added.

A brief summary of the geology of the various states, by Lindgren, forms an introduction to the catalogue proper.

A. D. B.

The Data of Geochemistry. By F. W. Clarke. Bull. No. 491, U.S. Geological Survey. Washington, 1911. Pp. 782.

A new edition of Bulletin No. 330, of the same title. A few revisions of minor importance are made to include new developments since the first edition.

A. D. B.

A CORRECTION

Berkeley, Cal.
May 14, 1912

Editors "Journal of Geology":

Dear Sirs: The January-February number of the *Journal of Geology* contains a paper by E. T. Dumble regarding some Tertiary and older deposits near Coalinga, Cal.

While in general he has given credit to the men whose work he has gleaned for his material, it is regrettable that some parts of the paper need correction. I have called his attention to this matter, but as nothing has been done I feel obliged to write to you myself.

On p. 32 there is a list of twenty-seven or more species the identification of which he has credited to me. I am compelled to state that his use of this list was premature and unauthorized, and it was not even contained in any of my private and confidential reports to him or to the Southern Pacific Company. I did indeed collect the fossils referred to, and had made a pencil list for purposes of study only, that was not designed for publication, as it needed confirmation or amendment. As it now stands it is incorrect in several of the identifications.

If Mr. Dumble had confided to me his desire to use this list, I would have furnished him one that was authentic and that would have been creditable to him and to myself, but as he did not, and as the matter stands, I do not wish to be sponsor for its accuracy.

F. M. Anderson

2604 Etna St.
Berkeley, Cal.

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NOVEMBER–DECEMBER, 1912

THE BANNOCK OVERTHRUST

A MAJOR FAULT IN SOUTHEASTERN IDAHO AND NORTHEASTERN UTAH

R. W. RICHARDS AND G. R. MANSFIELD

INTRODUCTION

In the course of a detailed geologic examination of portions of the Phosphate Reserve in southeastern Idaho during 1911 and 1912, the writers have had an opportunity to study an overthrust

fault which appears to be of unusual extent and magnitude. The purpose of this paper is to summarize the stratigraphy of the region and describe a portion of the great fault.

EARLIER WORK

The first geologic report on the general region is that of Peale (**18**) of the Hayden Survey.[1] The stratigraphy of the region has been modified only to the extent naturally incident to a more detailed study, but the newly described structural feature is scarcely of the same character. It appears that the stratigraphic discordance produced by the great thrust was recognized by the relations shown between the Jura Trias and the Carboniferous on Peale's map. The accompanying text, however, does not make reference to it. The 1909 report on the phosphate deposits by Gale and Richards (**10**) noted the existence of major thrusts in the Montpelier and Georgetown districts, but not enough of the surrounding country had been mapped at that time to suggest the relationship between the two. C. L. Breger (**6a**) in the same year noted the existence of a similar thrust along the valley of Crow Creek east of Preuss Range. The 1911 report (**19a**) on a portion of the Phosphate Reserve described a thrust fault which extended through the region west of Bear Lake and north into Nounan Valley. It remained, however, for the 1911 fieldwork in adjoining areas to develop sufficient data for a clearer understanding of the character of the thrust faulting.

STRATIGRAPHY

The rock formations of southeastern Idaho, and the adjoining portion of Utah, comprise a stratigraphic section in which every system from Middle Cambrian to Upper Jurassic or possibly basal Cretaceous is present unconformably overlain by Tertiary and Quaternary deposits. The latter rocks toward the south are sedimentary, but toward the north include extensive basaltic flows which are probably in part as late as the early Quaternary.

In the vicinity of Ogden, Blackwelder (**1**) has noted the presence of the Algonkian and Archean, while to the east of the Wyoming border Veatch (**24**) and Schultz (**20**) have described additional

[1] The blackface figures in parentheses following a name refer to the Bibliography at the end of this paper.

members of the Cretaceous system. These portions of the geologic column do not outcrop within the area with which this paper especially deals and are not included in the generalized section which follows.

GENERALIZED SECTION IN THE REGION OF THE BANNOCK THRUST

	FEET
Quaternary: Alluvium, travertine, basalt flows	
Tertiary (Pliocene?): Marls, marly limestone, and calcareous conglomerates	
Tertiary (Eocene): Sandstones, conglomerates, and limestones	
Unconformity.	
Cretaceous and Jurassic:	
Beckwith formation (24h) (6a), red shales, sandstones, and conglomerates	4,650
Jurassic: Twin Creek limestone (24i) (shaly limestone)	3,500
Jurassic or Triassic: Nugget sandstone (dark red to white sandstone and quartzite)	1,900
Triassic: (4) (22) (23)	
Ankareh shale (a red-bed horizon) shales and mottled limestone	670
Thaynes limestone, thin-bedded sandy limestone with heavy limestones (and locally conglomerate at top?)	2,000
Woodside shale, iron-stained calcareous shale with heavy limestones at top	1,000
Carboniferous:	
Permian?	
Phosphoria formation, 75 to 627 ft., averages	350
Rex chert member, 0 to 450 ft	
Pennsylvanian:	
Wells formation	2,400
Mississippian:	
Limestone, upper Mississippian, light gray, thick-bedded	1,300
Madison limestone, lower Mississippian, thin-bedded, dark gray to bluish-gray	1,000
Devonian: Jefferson limestone (14a) (19b)	750
Silurian: Limestone (13) (19c) (1a)	400
Ordovician: (1c) (19c) Quartzite and limestone	1,450
Upper Cambrian: (25) (26) St. Charles limestone (bluish-gray to gray arenaceous limestones, with some cherty and concretionary layers, passing at the base into thin-bedded gray to brown sandstone	1,197
Middle Cambrian:	
Nounan limestone (light gray to dark lead-colored arenaceous limestones)	814

	FEET
Bloomington formation (bluish-gray, more or less thin-bedded limestones and argillaceous shales; small rounded nodules of calcite are scattered irregularly through many of the layers of limestone)	1,162
Blacksmith limestone (gray arenaceous limestones in massive layers)	23
Ute limestone:	
Blue to bluish-gray thin-bedded fine-grained limestones and shales, with some oolitic, concretionary, and interformational conglomerate layers	731
Spence shale member (argillaceous shales)	30
Langston limestone (massive-bedded bluish-gray limestone with many rounded concretions)	30
Brigham quartzite (massive quartzitic sandstones)	1,000

Two of the formation names, those of the Wells and Phosphoria formations, and the name of one subordinate member, the Rex chert, appear for the first time in the above table. A discussion of the application of these names and detailed descriptions of the beds to which they are applied follow.

PHOSPHORIA FORMATION

The name of the Phosphoria formation is derived from Phosphoria Gulch, which joins Georgetown Canyon at a distance of 2.5 miles N. 16° W. of Meade Peak, Idaho, in which the formation is typically exposed.

The name of the Rex chert member is derived from Rex Peak in the Crawford Mountains, Rich County, Utah, where the chert forms an anticlinal cap. This locality has been described by Gale (10a) and the selection of the name for the member was originally made by him.

The following section is complete and representative of the formation as exposed in the region about Phosphoria Gulch, Idaho.

Complete Section of Phosphoria Formation, Including the Rex Chert Member, Measured in Section 12, T. 10 S., R. 44 E., and Phosphate Shales in Prospect Pit in Section 7 of T. 10 S., R. 45 E.

Description	Thickness Ft.	In.
Shale, black, cherty, weathers red-brown to purple	80	
Chert, in heavily iron-stained ledges	60	

Description	Thickness Ft.	In.
Limestone, gray, banded with ashy gray to black chert	100	
(Thickness of Rex chert member 240 feet)		
Shale, dark brown, weathers light brown, not fetid	1	0
Phosphate rock, gray, coarsely oolitic, with large pebbles, fossils, or oolites near base, some up to 2 inches in diameter; phosphoric acid 36.3 per cent	1	0
Shale, brown, finely oolitic	0	5
Phosphate rock, gray, coarsely oolitic pebbles or oolites up to 1 inch in diameter; phosphoric acid 36.7 per cent	0	8½
Shale, brown, weathers gray, in part finely oolitic	0	2½
Clay, yellow, weathered sandy, concretions up to ¼ inch, 3 grades into above shale	0	8
Phosphate rock, brown, medium oolitic, weathers gray; phosphoric acid 35.3 per cent	0	5
Shale, dark brown, phosphatic	0	2
Phosphate rock, dark brown, weathers gray, medium oolitic, single bed; phosphoric acid 29.4 per cent	0	5
Shale, brown, sandy with concretions up to 1 inch	0	5
Phosphate rock, gray, coarsely oolitic; phosphoric acid 35.9 per cent	1	2
Shale, dark brown to black, finely oolitic	0	3
Phosphate rock, coarsely oolitic; phosphoric acid 35.9 per cent	0	4
Shale, brown, sandy	0	1
Phosphate rock, medium oolitic	0	1½
Shale, brown, weathers gray with bluish tinge, finely oolitic	0	5
Phosphate rock, black, soft, medium oolitic	0	2
Shale, brown, calcareous	0	4
Phosphate rock, black, medium oolitic, soft	0	1
Shale, brown, oolitic in thin streaks	0	2
Phosphate rock, gray, coarse to finely oolitic; phosphoric acid 33.2 per cent	0	11
Phosphate rock, brown, finely oolitic, shaly	0	3
Phosphate rock, brown, medium oolitic	0	4
Shale, brown, with ¼-inch streak of oolitic rock near base	0	6
Phosphate rock, dark brown, coarse to finely oolitic, shaly in places; phosphoric acid 33.2 per cent	0	9
Phosphate rock, gray, coarsely oolitic, includes ½ inch of shale near base; phosphoric acid 37 per cent	1	1
Limestone, drab, impure	0	5
Phosphate rock, medium to finely oolitic	0	3

Description	Thickness Ft.	In.
Shale, brown, weathers gray	0	9
Phosphate rock, dark gray, coarsely oolitic, soft	0	2
Shale, brown	0	3
Phosphate rock, dark gray, coarsely oolitic, with several shaly partings less than $\frac{1}{8}$ inch thick; phosphoric acid 30 per cent	0	10
Limestone, lenticular	0	10
Phosphate rock, dark brown, medium to finely oolitic; phosphoric acid 26.1 per cent	9	8
Shale, black, in part finely oolitic	3	0
Shale, brown, partly weathered to clay	1	8
Shale, black, phosphatic, in part finely oolitic	6	6
Shale, brown, with concretions up to 2 inches in diameter	0	10
Shale, rusty brown to yellow, with a few concretions up to 1 inch in diameter	1	8
Shale, dark brown, with thin pebbly or concretionary bed at top, phosphatic in places	16	6
Pebbly or concretionary bed, concretions up to 2 inches in diameter	0	$3\frac{1}{4}$
Shale, brown	1	2
Shale, black to dark brown	0	9
Pebbly or concretionary layer, phosphatic	0	3
Shale, black, slightly oolitic	0	7
Shale, with pebbles or concretions up to 2 inches in diameter	0	6
Shale, brown, weathers to ochreous soil	3	4
Pebbly or concretionary bed	0	4
Shale, brown, weathers to ochreous soil	2	3
Pebbly or concretionary bed, phosphatic	1	0
Shale, brown, phosphatic	2	6
Shale, black, thin-bedded	0	6
Clay, ochreous	0	10
Shale, brown	1	0
Shale, black to light brown, slightly phosphatic	11	0
Limestone, broken, and intermixed with shale	6	0
Shale, broken, and weathered, only slightly phosphatic	21	0
Shale, black, phosphatic, finely oolitic, estimated to contain phosphoric acid 20 per cent	5	6
Shale, brown, weathers yellow, concretionary	1	0
Limestone, purplish-drab, lenticular	0	8
Shales, dark, broken, and weathered	15	0
Phosphate rock, broken, weathered drab	3	0
Soil, black, fetid	9	0

Description	Thickness Ft.	In.
Shale, black, phosphatic, finely oolitic	5	6
Limestone, dark, fetid	0	6
Shale, brown, somewhat phosphatic, contorted	15	0
Limestone, dark gray, dense ("Cap Lime" fossils)	3	0
Phosphate rock, dark brown, medium oolitic, soft, broken, apparently high grade*	7	0
Shale, brown, contorted, soft	1	0
Sandstone, white, calcareous, weathers buff. Top of Wells formation		
Thickness of phosphate shales	175	2½
Thickness of formation	415	

* Corresponds to bed from which sample 144S was taken. (10c)

The Phosphoria formation is the equivalent of the upper two members of the Park City formation (4a) (10b) as heretofore mapped in the phosphate district of Idaho and Utah, namely, the "overlying chert" and the phosphate shales. These members have also been recognized in the type section (4a) of the Park City in Cottonwood Canyon by H. S. Gale,[1] who reviewed the section in 1909 and noted the presence of phosphate rock. Gale regards the upper 129 feet of Boutwell's section (4a) as approximately equivalent to the chert member, and the underlying 112 feet as representing the phosphatic shale interval.

The remaining 194 feet is predominantly siliceous but contains a number of prominent limestone beds and is evidently comparable to the underlying siliceous limestone or calcareous sandstone of the phosphate districts.

The Park City formation was first referred by Boutwell to the Pennsylvanian, but in his later work on the district (5) has been referred as a whole doubtfully to the Permian. The lower portion contains the bonanzas for which the Park City district is famous and is therefore the essential part of the formation. This member is now upon additional faunal evidence referred to the Pennsylvanian.

The Phosphoria formation is also correlated with the upper portion of the Embar formation of Wyoming (8a) (9a) (3a), and

[1] Personal communication.

the phosphatic beds above the Quadrant formation of certain areas (11) (1) in southwestern Montana.

The Rex chert member is the conspicuous portion of the Phosphoria formation, and because of its superior hardness it stands out in salient topographic features. The phosphate shales on the other hand are comparatively non-resistant and the development of gulches along them is characteristic.

Locally 50 to 75 feet above the base the Rex chert gives way to gray limestone and in other places a dark gray to black or purplish flinty or cherty shale occupies the major portion of the Rex chert interval, but more generally the shaly facies is present near the top of the section and is occasionally with difficulty distinguished from the basal portion of the Woodside shale.

The Rex chert is generally non-fossiliferous but locally contains sponge spicules and casts of crinoid stems. Dr. Girty lists the following as the most characteristic species:

Productus multistriatus
Productus subhorridus
Spirifer aff. cameratus
Spiriferina pulchra
Composita subtilita var.

At a locality on Deer Creek in the Preuss Range Dr. Girty obtained the following fauna from the limestone facies of the Rex chert:

Amphoporella laminaria
Productus nevadensis
Productus eucharis
Productus multistriatus(?)
Camarophoria n. sp.

The basal portion of the Phosphoria formation consists of 75 to 180 feet of yellowish to brown phosphatic sandstones and shales with 1 to 3 economically important beds of rock phosphate, and occasional dark fetid limestones in beds and lenses ranging from 3 inches to 2 feet in thickness.

The fauna of the phosphate shales is an extensive one and has

been studied by Dr. Girty, who has selected the following characteristic list from his bulletin (12) on the subject:

Lingula carbonaria (?)
Lingulidiscina missouriensis
Chonetes ostiolatus
Productus geniculatus
Productus eucharis
Productus montpelierensis
Productus phosphaticus
Pugnax weeksi
Pugnax osagensis var. occidentalis
Ambocoelia arcuata
Leda obesa
Plagioglypta canna
Omphalotrochus ferrieri
Omphalotrochus conoideus
Hollina emaciata var. occidentalis

The distribution of the Phosphoria formation, so far as at present known, is limited to portions of southeastern Idaho, northeastern Utah, and western Wyoming.

WELLS FORMATION

The Phosphoria formation is normally underlain by 2,400 feet of sandy limestones, calcareous sandstones, and quartzites of somewhat variable character. These beds are here grouped in a formation whose name is derived from Wells Canyon in T. 10 S., R. 45 E., on the north side of which a detailed section was measured. The stratigraphic interval is probably the same as is represented by the Morgan, Weber, and a portion of the Park City formations of northeastern Utah. In the Idaho field, however, these rocks show such variable lithologic features that it has been found impracticable to apply successfully the names Weber and Morgan over a major portion of the area. Furthermore, Dr. Girty comments that there is no faunal assurance that these divisions as recognized are actually the equivalents of the formations in Weber Canyon, Utah. Faunal and structural grounds make it advisable to include

in the formation the limestone that normally underlies the phosphate shales and has hitherto been included in the Park City formation (10b) (19d).

The following section was measured at the type locality.

Geologic Section of Beds Exposed on North Side of Wells Canyon, Idaho

WELLS FORMATION

	FEET
1)	
Limestone, light brownish-gray, sandy *Squamularia* or *Composita*, possibly *Productus* crinoid stems	5
Chert, bluish-gray	1
Limestone, light brownish-gray, sandy	44
(2)	
Concealed	172
Sandstone, gray, calcareous, fine-grained in loose blocks and thin beds of quartzite or chert	150
Concealed	50
Sandstone, whitish, soft, in loose blocks, weathers like limestone, includes small quartz-lined geodes, poorly exposed, and partly represented by sandy soil and small fragments	350
Limestone, light bluish-gray, earthy with considerable dark chert	230
Sandstone, yellowish to red, in large blocks weathered rounded	100
Sandstone, whitish, rather soft	150
Quartzite, white, weathers pink to red, in large loose slabs, laminated and cross-bedded	200
Limestone, in part clear, in part cherty	200
(3)	
Limestone, dark gray with large chert concretions, fossil collection No. 45	200
Limestone, sandy, alternating with quartzite and clearer limestone	400
Sandstone, whitish, fine-grained, one bed	2
Sandstone, red in part, nearly quartzite, cross-bedded	100
Limestone, sandy, with quartz-lined geodes, one bed	3
Sandstone, white to reddish, soft, bears abundant *Schizophoria;* also represented by fossil collections Nos. 28 and 32 for near-by locality	35
Sandstone, one bed	2
Sandstone, thin-bedded; fossil collection 101c	6
Total thickness, Wells formation	2,400

UPPER MISSISSIPPIAN

	Feet
Limestone, earthy with chert in irregular concretions and streaks parallel to bedding	20
Limestone, light gray to whitish, thin-bedded; fossil collection 101	46
Sandstone, white, calcareous, bears large *Zaphrentoids*	14
Limestone, dark gray crinoidal, includes a *Martinia* horizon, about	100
Shale and reddish quartzite fragments, about	30
Quartzite, whitish, outcrops small and scattered, bears small *Zaphrentoids*	270
Concealed	200
Limestones, gray, in 1- to 3-foot beds, fossil collections	450
Base of upper Mississippian not exposed.	
Thickness of upper Mississippian exposed	1,130
Total thickness of section	3,530

It will be noted that in this section it is possible to subdivide the Wells formation into three portions, an upper calcareous sandstone or siliceous limestone, a middle sandy series, and a lower sandy and cherty limestone series, the lower two of which, however, do not correspond with the Weber and Morgan formations in Weber Canyon, Utah. Dr. Girty has recently reviewed the section at the latter locality and states that the order of lithologic succession is quartzite, calcareous sandstone, and red quartzite.

The variations which occur in the three portions of the Wells formation have been studied throughout the general area under discussion and in brief are as follows:

The upper limestone ranges from a maximum thickness of 75 feet down to a feather edge. It consists of a dense gray calcareous sandstone grading locally to siliceous limestone, which weathers into white massive beds that are topographically conspicuous as cliff makers. Bluish-white chert occurs in it in bands 2 inches to 1 foot thick and locally in ovate nodules. Toward the base the chert becomes more nodular and darker. Silicified fragments of brachiopods project in little crescents from the weathered surfaces of the limestone. This member is usually sparingly fossiliferous but, in the vicinity of Swan Lake, Dr. Girty reports a limited fauna (12*a*).

Local unconformity.—Locally the upper cliff-making limestone (1) is absent from the section and the Phosphoria formation then rests directly upon the more siliceous portion of the Wells formation, which in these places is composed of a breccia of chert and quartzite, similar to that described by Blackwelder (1d) under practically identical conditions, and it appears to the authors that this relationship represents another instance of a brief erosion interval in this part of the geologic section. Dr. Girty says (personal letter):

> The upper part of the Wells formation is usually nearly barren of fossils. Occasionally large *Producti* of the *semi-reticulatus* group are found as at Station 49 (T. 9 S., R. 45 E., sec. 35 SW $\frac{1}{4}$ SE $\frac{1}{4}$); rarely, however, in identifiable condition. Some well preserved examples obtained at this horizon near Swan Lake (Bannock County) show a form closely allied to *Productus Ivesi*. In that region also a small spiriferoid is very abundant, occurring as silicified fragments which project from weathered surfaces like small arched scales. When they can be identified these fossils belong to a species of *Squamularia* related to *S. perplexa*.

The middle portion (2) comprises 1,700 to 1,800 feet of sandy limestone with occasional thin beds of quartzite and sandstones, weathering white, red, or yellow, and forming smooth slopes with few projecting ledges. This portion is sparingly fossiliferous or non-fossiliferous. No fossils have yet been found in it. Locally a siliceous facies becomes strongly developed and this portion is then comparable with the Weber quartzite of Utah.

In the section under discussion sandy and cherty limestones with thin interbedded sandstones are conspicuous in the lower portion (3) of the Wells formation. The maximum observed interval of beds included in this facies is about 750 feet. Within a distance of 2 miles to the north the same interval was found on careful study to comprise only about 100 feet of beds. The cherty limestones are topographically important as ledge-makers and carry a fauna which, according to Dr. Girty, is probably similar in age to, although not specifically identical with, that found in the Morgan formation of Utah. Blackwelder (1e) has described the Morgan formation as composed of red sandstone, shale, and thin intercalated limestones, so that, lithologically, it is wholly distinct from the cherty limestones described above. Dr. Girty has con-

tributed the following faunal lists of collections from the Wells formation together with the following comments:

At the very base of the Wells formation a *Schizophoria* is often very abundant, apparently the same species as White identified in New Mexico as *S. resupinoides*? (Lot 101c). A short distance above a more varied fauna is usually found in which a large variety of *Spirifer rockymontanus*, the same which I identified in Colorado as *S. boonensis*, is specially abundant (Stations 28 and 32). Large branching *Stenoporas* related to *S. carbonaria* are also a feature of this fauna. Another phase of the lower Wells fauna is shown in Lot 33. In this assemblage of species *Marginifera splendens* is extremely common and large branching *Stenoporas* are also plentiful.

Lot 33

T. 9 S., R. 45 E., sec. 22, SW corner. From beds about 500 feet above base of Wells formation.

Stenopora Wellsiana	Productus Cora
Stenopora gracilis	Productus Nebraskensis
Stenopora Idahoensis	Productus semireticulatus
Stenopora ? sp.	Marginifera splendens
Derbya sp.	Spirifera rockymontanus

Lot 45

See section.

Zaphrentis Gibsoni	Productus semireticulatus
Monilipora Prosseri	Spirifer cameratus
Rhombopora lepidodendroides	Composita subtilita
Productus Cora	Euconospira n. sp.

Lot 28

T. 9 S., R. 45 E., sec. 35, SE ¼.

Spirifer rockymontanus
Myalina aff. Kansasensis
Aviculopecten sp.

Lot 32

Same locality as Lot 28 but from beds about 150 feet lower in the section.

Stenopora Idahoensis	Productus Cora
Stenopora ? sp	Spirifer rockymontanus
Batostomella ? sp.	Composita subtilita
Derbya sp.	Myalina sp.

Lot 101c

See section.

Schizophoria resupinoides ?

UPPER MISSISSIPPIAN LIMESTONE

The Wells formation in southeastern Idaho rests in apparent conformity upon limestone of upper Mississippian age. In Utah, however, Blackwelder (1f) has observed an unconformity at this position in the section. These limestones represent an unnamed formation comprising about 1,130 feet of beds. Lithologically they are massive gray, light to dark colored, weathering white to light gray. Locally a dark shale zone is developed near the top about 15 feet thick. In places also chert nodules with concentric and irregular forms and streaks of chert are present. The limestones are sometimes specked with siderite and seamed with calcite or aragonite, and are abundantly fossiliferous in some horizons. The fauna includes large cup corals with many fine septa, *Syringopora*, *Lithostrotion*, *Martinia*, and *Productus giganteus*. The Martinias are found in a bed near the top of the formation. A fauna collected at Ross Fork–Lincoln Creek (Idaho) by Meek (17) and later by Girty (19e) at Swan Lake which is comparable to that of the Spergen limestone of the central basin region of the United States is included at the Swan Lake locality in the upper Mississippian limestone interval.

The formation constitutes much of the Preuss Range and is well exposed in Meade Peak, the culminating point of that range. No complete section has been measured because of structural interruptions, but it is expected that future studies in the Ross Fork locality may afford a more favorable opportunity to obtain this, and the selection of a type locality for the formation is deferred for the present.

The authors are also indebted to Dr. Girty for the following faunal list and comments:

An interesting and varied fauna has in places been obtained from the upper part of the upper Mississippian. It is shown by the list of forms collected at Station 101. A short distance below this collection a new species of *Martinia* was found in countless numbers constituting a bed a foot thick. Very abundant also in local occurrences is a small variety of *Productus giganteus*. Large Zaphrentoid corals are likewise a feature of the upper Mississippian, often occurring associated with *Syringopora* and one or more species of *Lithostrotion*. These colonies are sometimes of great size. Here too is sometimes found an

assemblage of small forms more or less related to the "Spergen" fauna reported by Meek from Ross Fork. The horizon of all these rather strikingly different facies appears to be below that of Station 101.

101

Zaphrentis sp.	Edmondia ? sp.
Stenopora sp. a	Conocardium sp.
Stenopora sp. b	Schizodus sp.
Stenopora ? sp.	Sphenotus sp.
Batostomella ? sp.	Myalina aff. Sanctiludovici
Rhombopora ? sp.	Leptodesma aff. Spergenense
Productus semireticulatus	Sulcatipinna Ludlowi ?
Productus semireticulatus var.	Parallelodou ? sp.
Productus pileiformis	Cypricardinia ? sp.
Productus punctatus var.	Aviculipecten sp. a
Productus aff. longispinus	Aviculipecten sp. b
Diaphragmus elegans	Aviculipecten sp. c
Camarophoria Wortheni	Pseudomonotis ? sp.
Dielasma sp.	Laevidentalium venustum ?
Spirifer striatus ?	Naticopsis sp.
Spirifer increbescens ?	Straparollus similis var.
Spiriferina sp.	Bulimorpha aff. elongata
Composita trinuclea ?	Griffithides sp.
Edmondia sp.	Phillipsia sp.

THE BANNOCK FAULT

The field seasons of 1909 and 1910 led to the recognition by members of the U.S. Geological Survey of important thrust faults in southeast Idaho (10d, e) and adjacent parts of Utah (10f, g). In 1911 the study of the great fault east of Georgetown, Idaho, led to the view that several of these faults, formerly considered distinct, are in reality parts of one great overthrust, for which the name Bannock is proposed, from Bannock County, Idaho, where the fault is strikingly developed. The individual faults which have been thus united and the facts upon which the interpretation rests are described below (Fig. 1).

GEORGETOWN FAULT

In 1909 a thrust fault involving the superposition of Mississippian limestones upon rocks of Jurassic or Cretaceous age was recognized by Gale (10d) in Georgetown Canyon about 5 miles

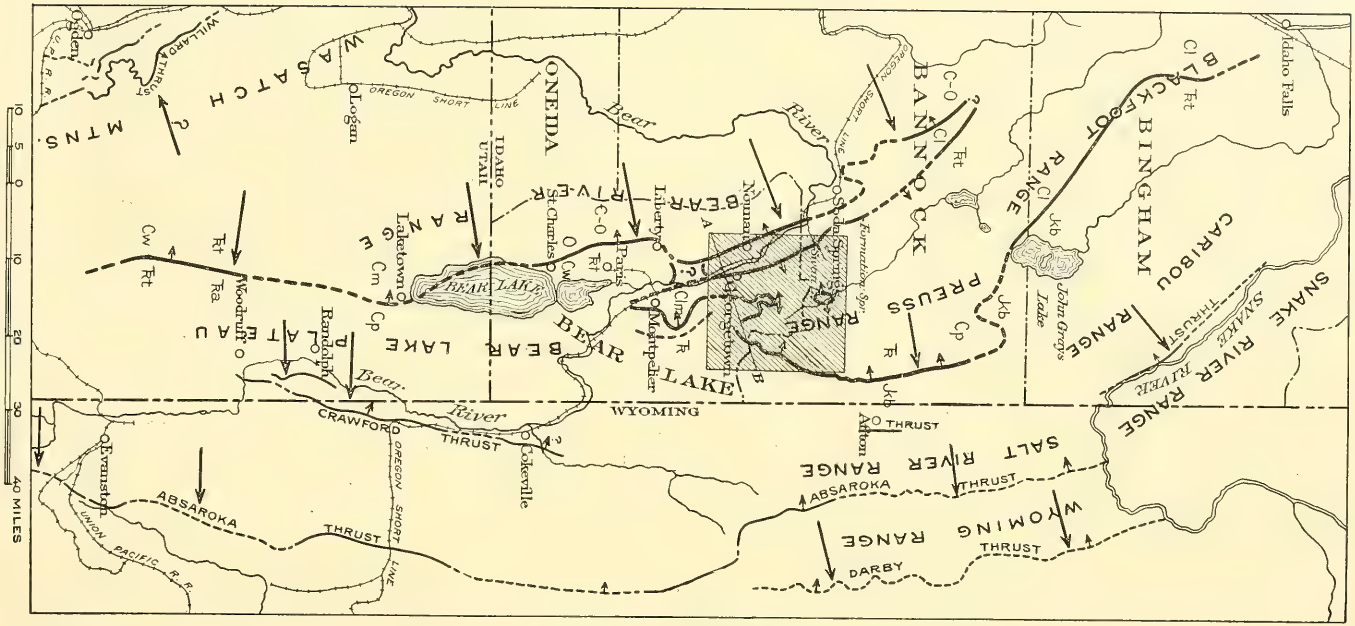

FIG. 1.—Sketch map of southeastern Idaho and portions of adjacent states.

Explanatory notes.—The trace of the Bannock thrust is shown by the heavy broken line. The shaded area is more fully illustrated by the stereogram, Fig. 2, and the geologic structure along the line *A–B* is represented by Fig. 5. The letter symbols signify as follows:

Jkb, Beckwith formation; *Jtc*, Twin Creek limestone; *Tr*, Triassic undifferentiated; *Trn*, Nugget sandstone; *Tra*, Ankareh shale; *Trt*, Thaynes limestone; *Cp*, Phosphoria formation; *Cw*, Wells formation; *Cl*, Upper Mississippian limestone; *Cm*, Lower Mississippian (Madison) limestone; *Clm*, Mississippian undifferentiated; *O*, Ordovician; *C*, Cambrian.

northeast of the village of Georgetown (see map). In 1911 this district was visited by the writers and the fault was studied and mapped in greater detail. From the north fork of Georgetown Canyon, where the fault emerges from beneath the late conglomerates, its sinuous course was followed across the Preuss Range into Crow Creek as far as the mouth of Sage Creek (Fig. 2), a distance of approximately 30 miles, and here it appeared to continue northward.

The sinuosity of the fault trace is due not only to erosion but to deformation as well. In the north fork of Georgetown Canyon an anticlinal axis has arched the thrust surface or plane so that it has been partly removed and the underlying Nugget and Twin Creek formations are exposed in the valley, while long strips of heavy Mississippian limestone reach down the spurs of the ridges like the fingers of some giant hand (see Figs. 1 and 2). A synclinal axis depresses the thrust surface where it passes beneath the Preuss Range in the headwaters of Montpelier Creek. In this region there is a marked contrast between the massive and castellated limestones of the Mississippian that constitute the upper part of the ridge and the chippy and shaly limestones of the Twin Creek formation that are exposed along the lower slopes of the valley side.

In Georgetown Canyon and southeast across the Preuss Range (Fig. 3) the same relations obtain. The underlying Twin Creek beds are folded so that the stratigraphic throw cannot be obtained with accuracy, but the missing formations, including Pennsylvanian to Triassic (?) rocks (Nugget), represent a minimum vertical displacement of about 8,500 feet. Eastward the throw apparently diminishes partly by the agency of branching faults and partly on account of the folded structure of the rocks in the upper block.

The general trend of the trace of the fault appears to be a few degrees to the west of north and the direction of thrust a little to the north of east. The dip of the fault surface gives little aid in determining the direction of movement because of its present deformed condition. The older rocks, however, lie to the west and the thickness of the thrust block appears to increase in that direction.

The distance, perpendicular to the general trend, between the

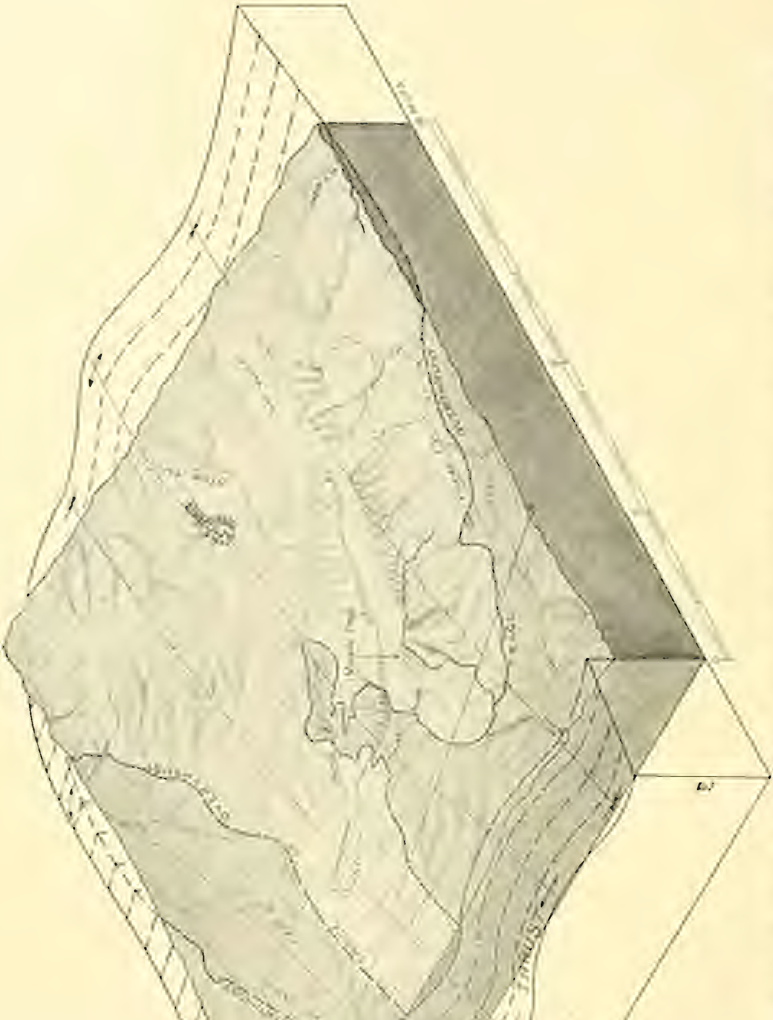

Fig. 2.—Stereogram of a portion of the region including the trace of the Bannock thrust. The location of the area is shown on Fig. 1. The direction of movement was in general from west to east and approximately parallel to the line of the structure section *A–B*.

westernmost observed portion of the fault trace in Georgetown Canyon and the easternmost portion of that trace in Crow Creek is about 12 miles. It appears, therefore, that the heave may be equal at least to that distance.

In the ridge west of Slug Creek (Fig. 2) an elongate area apparently surrounded by a fault boundary is interpreted as an anticlinal portion of the main thrust, or of a subordinate thrust, unroofed by erosion so that the underlying block is exposed through a "window" or "fenster." The position of this window with reference to the anticline in the north fork of Georgetown Canyon is favorable to this interpretation.

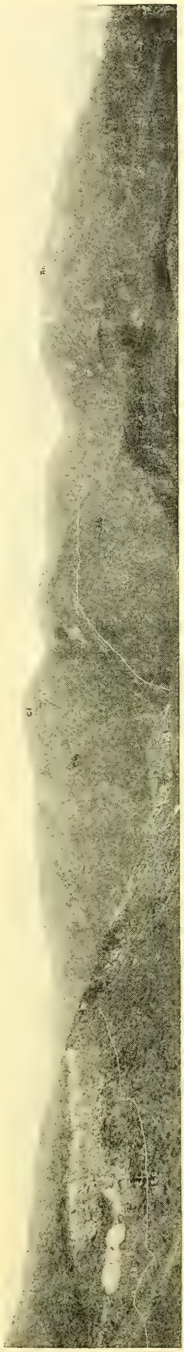

Fig. 3.—Panorama from south-pointing spur on hill north of Georgetown Canyon (see Fig. 2) looking northeast to nearly due south. Meade Peak is situated to the left of the middle of the picture. The trace of the Bannock thrust and a sharp drag fold in the overthrust Mississippian limestone is shown in the left foreground. The trace of the Bannock fault is also indicated on the divides between Georgetown and South Canyons, the latter and Dunn's Canyon; thence to the head of the latter where it crosses to the head of Montpelier Creek where it appears in Fig. 4. For explanation of letter symbols, see Fig. 1.

JOHN GRAYS LAKE AND BLACKFOOT FAULTS

Reconnaissance by the senior author and Dr. A. R. Schultz of the U.S. Geological Survey northward from the area above described and in the vicinity of John Grays Lake developed the presence of a thrust fault of similar magnitude in that region. While this fault has not been traced directly into the Georgetown fault, from the position of the thrust and its general relations it is interpreted as a continuation of that fault. The northwestward extension of the John Grays Lake fault is concealed by flows of basalt. A similar thrust was recognized in the same reconnaissance in the Blackfoot Range. The alignment and the

effects of the two are practically identical and they clearly may represent the same crustal break.

MONTPELIER FAULT

The work of Gale and Girty in 1909 (10e) in the Montpelier district demonstrated the existence near Montpelier of a great thrust fault in which heavy Mississippian limestones from the west were overthrust upon Lower Triassic formations, the Woodside, Thaynes, and Ankareh. Northward, southward, and westward the fault trace passes beneath the cover of late deposits. To the south no further indication of thrust faulting has been recognized on the east side of Bear Lake Valley, though a normal fault of considerable importance lies along the east shore of Bear Lake. To the north, however, at no great distance lies the Georgetown thrust fault, in which the structural relations of older and younger rocks are closely similar to those of the Montpelier district. There seems therefore good reason for the supposition that the two faults are continuous beneath the covering of alluvium and Tertiary deposits.

SWAN LAKE FAULT

In 1910 the writers found a thrust fault along the west base of the Aspen Range east of Bear Lake Valley, particularly well developed near Swan Lake, about 7 miles southeast of Soda Springs (Fig. 1). Here similar conditions hold and Carboniferous limestones lie upon Triassic rocks. The dip of the fault plane here appears to be eastward but this feature may, as in the Georgetown block, be due to deformation of the fault plane, for the source of the older rocks appears to be to the west as in the Georgetown fault. The trace of the Swan Lake fault is marked by the occurrence of sulphur and calcareous springs and also by great deposits of travertine, of which Formation Spring, 3 miles northeast of Soda Springs, with its basins and terraces is a beautiful example. In the 1910 report (19f) it was argued that these springs marked the trace of a normal fault that cut the Carboniferous thrust block along the west base of the Aspen Range. In the light of the later studies in the Georgetown region it seems probable that all the features ascribed to the normal fault can be better explained by the deforma-

tion of the thrust fault surface here described. Southward deposits of travertine occur at intervals along the base of the range to a point opposite the mouth of Three Mile Creek, about 3 miles south of Georgetown. It seems probable therefore that the Swan Lake fault is closely related to the Georgetown fault and may represent a part of the same thrust plane so deformed as to constitute the west limb of a gentle syncline. This interpretation is shown on the map and stereogram (Figs. 1 and 2).

WEST BEAR LAKE FAULT

In 1910 the writers encountered a great thrust fault on the west side of Bear Lake near Paris. This fault was followed southward beyond St. Charles, and northward beyond Soda Springs, a distance of over 45 miles (Fig. 1). The fault surface or plane appears to dip gently west. The upper block comprises rocks of Cambrian to Devonian age, while the underlying rocks are Pennsylvanian Lower Triassic (Upper Wells to Thaynes). Hence the structural relations here are similar to those of the Georgetown–Swan Lake fault except that the range of the formations involved and the magnitude of the throw are somewhat greater. The presence of two such great and similar overthrusts upon opposite sides of Bear River Valley, together with the known fact of deformation in the eastern fault, leads to the interpretation that the West Bear Lake fault and the Georgetown–Swan Lake fault are parts of the same great thrust fault, and that they have been separated by the partial erosion of an anticlinal fold in the thrust plane (see map and stereogram, Figs. 1 and 2).

FAULTS NEAR LAKETOWN AND WOODRUFF, UTAH

In 1909 Gale and Richards reported the existence of thrust faults at Laketown (10f) and near Woodruff (10g), Utah. These faults also represent movements from the west and bring rocks of Mississippian or greater age over younger formations. It is not possible to follow these faults and to trace their connection with each other and with the West Bear Lake fault to the north because of the extensive development of Tertiary beds (Eocene) in the intervening area. Their position and structural relations lend support to the view that they represent the southern continuation

of the great thrust fault to the north. This interpretation is tentatively shown on the map (Fig. 1).

MAGNITUDE OF THE BANNOCK FAULT

The trace of the Bannock fault as above constituted with its major sinuosities as represented on the map (Fig. 1) extends approximately 270 miles from the vicinity of Woodruff, Utah, to the region north of John Grays Lake. The general trend of the fault trace is slightly west of north and the direction of movement must have been perpendicular to that trend and, as indicated in the above discussion, was probably from the west.

The structure of the underlying block, as shown in the mountainous portion of the region, comprises a series of folds, for the most part close and overturned toward the east. Figs. 4 and 5 (photo and cross-section) show folds in the overridden Twin Creek limestone in the upper waters of Montpelier Creek. The large alluvial area at the north end of Bear Lake Valley and extensive areas masked by Tertiary detrital deposits render the structure of the underlying rocks problematical. This structure must, however, be determined before the place of origin and the amount of displacement effected by the thrust can be satisfactorily determined. It has been pointed out that in the Georgetown Canyon region the missing formations indicate a minimum vertical displacement in that locality of about 8,500 feet. On the west side of Bear Lake where Cambrian or Ordovician quartzites overlie Woodside and Thaynes formations the minimum throw on the same basis would probably be at least 12,000 feet.

The structure section (Fig. 5) along the line *A–B* contains one of the best exposures of the underlying block and a minimum amount of cover. The section represents the supposed attitude of the deformed fault plane.

Cambrian rocks nowhere rise to the level of the fault surface in the region traversed by the section. It therefore follows that the Cambrian portion of the overthrust block at the extreme west end of the section must have been derived from a fold lying to the west of this point, the structure of which is concealed by the overthrust block.

A clue to the minimum horizontal displacement is suggested by the possibility that the Mississippian limestones of the western

fold of the structure section may represent the source of the overthrust mass of these formations that lies some 12 miles to the east. The source can certainly not be nearer, for the Mississippian limestones do not rise to the level of the fault plane in any of the folds farther east in this district. Furthermore, the size of the Mississippian limestone mass, as inferred from known conditions north and south of the line of the section, suggests that either the westernmost fold of the section has not been made large enough, or that the source was a more westerly fold. These considerations make it apparent that the amount of horizontal displacement is not less than 12 miles.

Another measurement of the horizontal displacement may be expressed by a line drawn perpendicular to the general trend of the fault trace and extending from the westernmost point on the trace

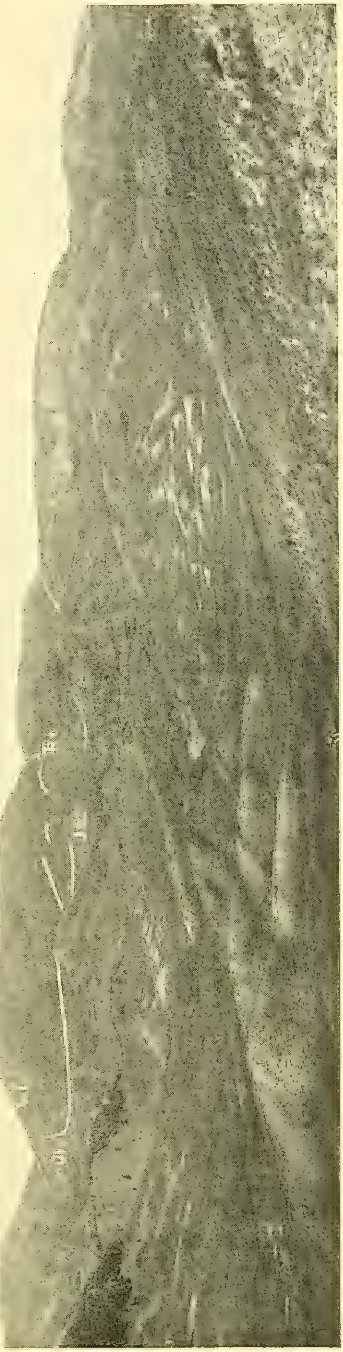

FIG. 4.—Panorama from point near the southeast corner of area shown in Fig. 2. The direction of view is northwesterly. The southern tip of the uneroded portion of the overthrust block and the position of the subordinate branch fault, together with the approximate character of geologic discordance is indicated. A syncline and parallel anticlines are visible in the foreground (in the Twin Creek limestone). For meaning of letter symbols see Fig. 1.

to the easternmost point on the east margin of the fault block. The length of such a line is about 35 miles. This, however, neglects the recession produced by erosion along the east margin of the fault block.

AGE OF THE THRUST

The youngest rocks involved in the faulting are sandstones of the Beckwith formation, which may in part be of early Cretaceous age. The oldest rocks which have been found concealing its trace are the conglomerates of the Almy formation (24a) which represents the basal portion of the Wasatch group as defined by Veatch.

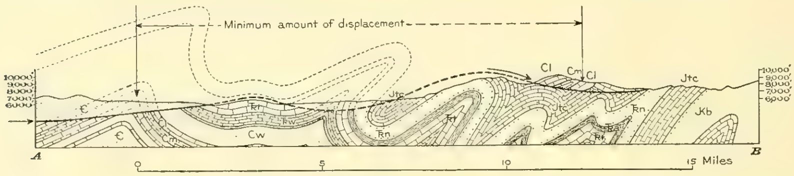

FIG. 5.—Geologic structure section along the line *A–B* in Figs. 1 and 2. The meaning of the letter symbols is explained under Fig. 1 with the exception of *Trw*, which represents Woodside shale.

The possible range of age is then from late Cretaceous to early Eocene, and it is probable that the faulting may have occurred during the interval represented by the unconformity between the Adaville (24b) and Evanston (24e) formations of Veatch.

DEFORMATION OF FAULT PLANE

The arrow points distributed along the fault trace on the map (Fig. 1) indicate in a general way the present attitudes of the fault plane. The stereogram (Fig. 2) shows the nature of these folds as present and reconstructed for a block 18 miles square. The location of Fig. 2 is indicated by the shaded area on the map, Fig. 1. The plications comprise two anticlines, two synclines, and portions of the adjoining folds. The trend of these folds is slightly west of north. Erosion has completely unroofed the western anticline and has made a considerable start on the second. The exposure of a closed area of the underlying block through a "window" or "fenster" in the overthrust has already been mentioned.

Deformation of fault planes is usually attributed to a renewal of the compressive forces and the folding tends to continue along

the lines formerly developed. In the vicinity of Meade Peak near the south end of the Preuss Range, where the best opportunity has been found to study the character of the deformation, a well defined syncline has been developed almost directly under a sharp anticline in the overlying beds. The question is raised as to whether or not the deformation of the plane of the thrust may be due to the load of the overlying anticlinal mass rather than lateral pressure. The dip of the fault plane that branches from the main fault and extends under the east flank of Meade Peak (Fig. 4) is steep and in places appears to be inclined westward. These facts are regarded as unfavorable to the latter view.

PARALLEL ASSOCIATED THRUSTS

Extensive overthrust faults are by no means a novel feature of the region, and faults have been previously described immediately east and west of the trace of the Bannock. The position of these faults has been shown upon Fig. 1.

Western Wyoming.—Peale (18a), Veatch (24d), and Schultz (10a) have described portions of the great Absaroka thrust, the trace of which lies about 8–25 miles east of the state boundary.

The throw in two localities (24e) described by Veatch is over 15,000 and 20,000 feet respectively. In the latter place rocks of Triassic age rest upon rocks of middle Cretaceous age—specifically, the Thaynes limestone upon the Oyster Ridge sandstone member of the Frontier (24f) formation.

North of these areas Schultz reports that the throw is of the same amount. The Darby, another overthrust which has been mapped by Schultz (20b), has a maximum exposed horizontal displacement of 3 miles. Labarge Mountain, which is a part of the overthrust block overlying the plane of the Darby fault, is composed in part of rocks of Cambrian age. This is, according to Schultz,[1] the easternmost exposure of the Cambrian rocks which make up the greater part of the Bear River Range in Utah and Idaho, a distance of over 50 miles to the west. It is possible, then, that the rocks present in Labarge Mountain may have been derived from the region of the Bear River Range.

[1] Personal communication.

Between the Absaroka and Bannock thrusts there appears to be at least one extensive parallel thrust zone. The Crawford thrust (24g) or the parallel fault (10h) immediately to the west may represent the southern end, while the faults reported in the vicinity of Cokeville (10i), Afton (18b), and observed by the senior author and A. R. Schultz in the Snake River region, represent the northward continuation.

These overthrusts are held by Veatch (24) and Schultz (20) to have occurred near the close of the Cretaceous period.

Ogden, Utah.—In the vicinity of Ogden, Blackwelder (1) has recently described several overthrusts. The major of these, the Williard thrust, causes lower Algonkian slates and graywackes to overlie Cambrian and Carboniferous sediments. The thrust plane has an average easterly dip of 15° but locally is as high as 50°. Blackwelder holds that subsequent deformation of the plane has been slight and that the apparent distortion is mainly due to original undulation. The maximum exposed horizontal displacement of 4 miles is probably only a small fraction of the total heave. The direction of movement is naturally inferred to be westward from the inclination of the thrust plane. The writers suggest that broader regional studies are necessary before a westward direction of movement can be regarded as proved. It may well be that the present eastward inclination of the fault plane is the result of deformation, as is clearly the case in many places along the trace of the Bannock thrust.

Blackwelder described two other thrusts in the Ogden region, one which produces discordant relations within the Cambrian, and another which causes Carboniferous limestone to overlie Cambrian shales and quartzites.

Blackwelder concludes that the Ogden thrusts "are of Cretaceo-Eocene age."

RELATION OF BANNOCK THRUST TO PARALLEL THRUSTS

The fact that the several portions of the Bannock thrust as described have been isolated by erosion and disguised by subsequent deformation makes it possible that future study will show that outliers of the overthrust block lie to the east of the margin of the Bannock thrust as at present defined.

The additional possibility should not be overlooked that the known thrusts of probably identical age lying to the east and to the west may in reality bound portions of the same overthrust mass which have been isolated by erosion.

North of the region of the Bannock thrust and in what appears to be the same zone of crustal readjustment, faults of great magnitude are known to exist. One in Montana, on the east side of the Bitterroot Mountains, has been described by Lindgren (15), another in the vicinity of Philipsburg, Montana, by Calkins (7), and the Lewis thrust in northern Montana and southern British Columbia which has been described by McConnell (16), Willis (27), and more recently studied by Campbell.

The last two are clearly thrusts the planes of which have been deformed, and all three may eventually prove features of the same tectonic event as the Bannock and the parallel faults toward the south, although it appears that if Willis' age determination of the Lewis thrust is correct, the Bannock overthrust occurred at an earlier geologic date.

It is apparent, however, that a close approximation of the actual and relative ages of the several faults awaits more extended geologic studies in the Rocky Mountain region.

BIBLIOGRAPHY

1. Blackwelder, Eliot. "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. America,* XXI (1910), 517–42; (*a*) p. 523; (*b*) p. 527; (*c*) p. 526; (*d*) p. 532; (*e*) p. 529; (*f*) p. 528.
2. ———. "Phosphate Deposits East of Ogden, Utah," *Bull. U.S. Geol. Survey No. 430* (1910), pp. 536–51.
3. ———. "Reconnaissance of Phosphate Deposits in Western Wyoming," *Bull. U.S. Geol. Survey No. 470* (1911), pp. 452–81; (*a*) p. 459.
4. Boutwell, J. M. "Stratigraphy and Structure of the Park City Mining District, Utah," *Jour. Geology,* XV (1907), 434–58; (*a*) p. 444.
5. ———. "Geology and Ore Deposits of the Park City District, Utah," *Prof. Paper U.S. Geol. Survey* (in preparation).
6. Breger, C. L. "The Salt Resources of the Idaho-Wyoming Border, with Notes on the Geology," *Bull. U.S. Geol. Survey No. 430* (1910), pp. 555–69; (*a*) p. 562.

7. Calkins, F. C., and Emmons, W. H. "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," *Prof. Paper U.S. Geol. Survey No. 78* (in press).

8. Darton, N. H. "Geology of the Bighorn Mountains," *Prof. Paper U.S. Geol. Survey No. 51* (1906); (*a*) p. 35.

9. ———. "Paleozoic and Mesozoic of Central Wyoming," *Bull. Geol. Soc. America*, XIX (1908), 403–70; (*a*) p. 416.

10. Gale, H. S., and Richards, R. W. "Phosphate Deposits in Idaho, Wyoming, and Utah," *Bull. U.S. Geol. Survey No. 430* (1910), pp. 457–535; (*a*) p. 513; (*b*) p. 475; (*c*) p. 477; (*d*) p. 482; (*e*) p. 490; (*f*) p. 523; (*g*) p. 527; (*h*) p. 514; (*i*) p. 506.

11. ———. "Rock Phosphate near Melrose, Montana," *Bull. U.S. Geol. Survey No. 470* (1911), pp. 440–51; (*a*) p. 444.

12. Girty, G. H. "Fauna of the Phosphate Beds of the Park City Formation in Idaho, Wyoming, and Utah," *Bull. U.S. Geol. Survey No. 436*, 1910; (*a*) p. 6.

13. Kindle, E. M. "Occurrence of the Silurian Fauna in Western America," *Am. Jour. Sci.*, 4th ser., XXV (1908), 125–29.

14. ———. "Fauna and Stratigraphy of the Jefferson Limestone in the Northern Rocky Mountain Region," *Bulletins of American Paleontology*, IV, No. 20 (1908).

15. Lindgren, Waldemar. "Geological Reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho," *Prof. Paper U.S. Geol. Survey No. 27* (1904); (*a*) pp. 26–27.

16. McConnell, R. G. "Report on Geological Structure of a Portion of the Rocky Mountains, Accompanied by a Section Measured near the Fifty-first Parallel," *Canada, Geol. and Nat. Hist. Survey, 1886, Report D* (1887).

17. Meek, F. B. "Preliminary Paleontological Report," *Sixth Ann. Rept. U.S. Geol. Survey Terr.* (1872), pp. 470–71.

18. Peale, A. C. "Report on Geology of Green River District," *Eleventh Ann. Rept. U.S. Geol. Survey Terr. for 1877* (1879), pp. 509–646; (*a*) p. 536; (*b*) p. 546.

19. Richards, R. W., and Mansfield, G. R. "Preliminary Report on a Portion of the Idaho Phosphate Reserve," *Bull. U.S. Geol. Survey No. 470* (1911), pp. 371–439; (*a*) p. 397; (*b*) p. 383; (*c*) p. 382; (*d*) p. 385; (*e*) p. 384; (*f*) p. 398.

20. Schultz, A. R. "Coal Fields in a Portion of Central Uinta County, Wyo.," *Bull. U.S. Geol. Survey No. 316* (1906), pp. 212–41; (*a*) p. 217; (*b*) Plate 8.

21. ———. "Geography and Geology of Part of Uinta County, Wyo.," *Bull. U.S. Geol. Survey* (in preparation).

22. Smith, J. P. "Distribution of the Lower Triassic Faunas," *Jour. Geology*, XX (1912), 13–20.

23. ———. "Comparative Stratigraphy of the Marine Trias of Western America," *Proc., Cal. Acad. Sci.*, 3d ser., I (1904), 323–30.

24. Veatch, A. C. "Geography and Geology of a Portion of Southwestern Wyoming, with Special Reference to Coal and Oil," *Prof. Paper U.S. Geol. Survey No. 56* (1907); (*a*) p. 89; (*b*) p. 72; (*c*) p. 76; (*d*) p. 109; (*e*) p. 110; (*f*) p. 65; (*g*) p. 112; (*h*) p. 57; (*i*) p. 56.

25. Walcott, C. D. "Cambrian Faunas of North America," *Bull. U.S. Geol. Survey No. 30* (1886).

26. ———. "Cambrian Sections of the Cordilleran Area," *Smithsonian Inst., Misc. Coll.*, LXIII (1908), 167–230.

27. Willis, Bailey. "Stratigraphy and Structure of the Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. America*, XIII (1902), 305–52.

28. ———. "Überschiebungen in den Vereinigten Staaten von Nordamerika," *Congr. geol. intern., Compte Rendu IX Sess., 1903* (1904), pp. 529–40.

29. Woodruff, E. G. "The Lander Coal Field, Wyoming," *Bull. U.S. Geol. Survey No. 316* (1907), pp. 242–43.

GLACIATION IN THE TELLURIDE QUADRANGLE, COLORADO

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PART III

DESCRIPTION OF DEPOSITS OF EARLIER DRIFT

RIDGES EAST AND WEST OF EDER CREEK

On the east side of Eder Creek, from the edge of the southern part of the ridge down to within 200 or 300 feet above the stream, and thence northward in an irregular belt a quarter of a mile or less from the stream, the surface shows plentiful bowlders up to 15 feet in diameter. These large bowlders are mostly rather rough and angular, and consist chiefly of Potosi rhyolite or Silverton, and Telluride. On the top of the ridge, the deposit contains fewer bowlders at the surface, their size is on the average less, and a greater variety of rocks is included—San Juan being noticeably more abundant than on the slope to the west. A striated bowlder was found on the top of the ridge at 10,500 feet. Farther north, within a quarter of a mile of the col that connects this ridge with the mountain to the north, an exposure on the west side of the ridge at about 10,300 feet shows an unstratified deposit of clay, gravel, and bowlders in variety; on some of the bowlders faint striations were observable. On the east side of the ridge, glacial drift including well-striated bowlders occurs down to about 10,400 feet, joining here with the hummocky, irregular topography which has already been described.

The boundaries of the area just described are not clearly marked on all sides, but are approximately as mapped.

This area is classed as older drift because of (1) its topographic location, far above the clearly marked limit of the recent glaciation: (2) its composition, differing as it does from the more recent drift in the presence on the surface of many large, weathered bowlders,

including Potosi rhyolite, which is unknown in the more recent drift except in small fragments; and (3) the generally more weathered appearance of the surface, especially as compared with that of the more recent drift in the valley of Eder Creek below.

The ridge west of Eder Creek above the limit of the ice in the San Miguel valley, and up to about 10,000 feet, contains on the surface fragments of rock in variety including blocks of Potosi rhyolite up to 18 feet in diameter. At several places holes a foot or two in depth expose rounded, as well as angular, bowlders in variety. No cases of undoubted striation were observed. In the forest-covered portion, but few bowlders or rock fragments could be seen; on slopes free from trees numerous small fragments, including rhyolite, occur.

On the east, the area marked by rhyolite bowlders and fragments joins the deposits made by the glacier of the more recent epoch; on the west, it extends almost to the bottom of the next small valley, about a half-mile distant.

IN THE VALLEY OF REMINE CREEK

The valley of Remine Creek is irregularly fan shaped, with low, round-topped ridges radiating from the lower part of the valley above Keystone, until they are lost in the nearly even steep slope which stretches from timber line up to the very crest of Iron Mountain. Neither on the face of the mountain to the north, nor in the valleys below is there evidence of glaciation of the more recent epoch. Exposures of drift, with a few striated bowlders, are found at the two points indicated on the map, viz.: (1) on the eastern side at elevation 9,700 to 9,900 feet, and (2) on the western side at 9,400 to 9,700 feet. At both of these points, the exposure is due chiefly to the slipping of the surface layers on a steep slope of a hill 50 to 100 feet high; bowlders in variety up to 4 or 5 feet in diameter occur, mostly well rounded, but rarely distinctly striated. Large Potosi rhyolite bowlders do not occur here as in the areas near Eder Creek.

These two drift areas in the valley of Remine Creek are referred to the earlier epoch of glaciation because of their isolated position; that is, the absence of evidence of glaciation in other parts of the

valley, together with the generally mature stage of erosion of the whole basin.

ALONG DEEP CREEK

A little more than half a mile below the junction of the east and the west forks of Deep Creek, deposits occur estimated at not less than 30 to 40 feet in thickness at a maximum. As shown on the accompanying map, they lie chiefly on the east side of Deep Creek. In topography, the surface is in part irregular, but part shows some ridges approximately parallel to the tributaries of Deep Creek from the east. In composition, the deposit contains bowlders in variety up to 3 or 4 feet in diameter, many of them rounded; none with distinct glacial striations were found.

The deposits are classed as glacial on the evidence of the topography, the heterogeneous composition, the unstratified arrangement, and the rounded, subangular forms of the included bowlders. It is classed as older drift because of its disposition, discordant with the clearly marked deposits of the recent epoch farther up the stream, and because of the absence of evidence of recent glacial action in the upper part of the valleys of the tributaries next south of the east fork of Deep Creek.

ON THE WEST SIDE OF PROSPECT CREEK

At elevation 9,900 to 10,000 feet along the road parallel to Prospect Creek, glacial drift containing striated bowlders occurs at intervals for nearly a quarter of a mile. These exposures are on the southwest-facing slope of a round-topped ridge which separates the valley of Prospect Creek from that of one of its tributaries. The slope is here wooded, and the composition of the surface deposits is largely obscured.

NEAR THE JUNCTION OF THE TWO BRANCHES OF TURKEY CREEK

Deposits near the junction of the two branches of Turkey Creek occur as follows:

1. At a point about one-fourth of a mile above the junction of the two branches, glacial débris extends 20 to 30 feet up from the stream on the north side.

2. Just above the junction of the two branches a small accumulation of glacial débris lies between the two streams, joining the

ridge which extends to the southeast from this point. Just below the junction, on the north side of the stream, a distinct ridge begins, which is continuous to the edge of the glacial deposits made by the glacier moving down Lake Fork. The crest of this ridge is from 30 to 40 feet above the stream, and numerous sections show it to contain bowlders in variety such as occur to the east. The deposits made by the Lake Fork Glacier in the more recent epoch are characterized by an abundance of the light-colored granitic phase of the diorite-monzonite intrusions farther up the valley; but this diorite-monzonite is absent from the morainal ridge north of Turkey Creek just below the junction of the two branches. At the point where the stream crosses the eastern edge of the moraines of the Lake Fork Glacier, an exposure of drift on the south side of the stream about 75 feet in height shows diorite-monzonite bowlders in abundance and near the top of the exposure on the east side some stratified drift.

Above the deposit (1), named above, the course of the north branch of the stream lies in a narrow, steep-sided channel, in which are exposed enormous masses of Telluride and San Juan rocks tilted at angles up to 45° upstream; no recognizable drift occurs near the stream until the boundary of the moraines already described is reached, at elevation 10,100 feet. The valley of the south branch of Turkey Creek above the junction has a gradient less steep than the north branch, but in this direction also no drift is recognizable until at the mouth of the first small tributary from the east an alluvial fan shows bowlders evidently derived from the edge of the glaciated tract a half-mile to the east. A little farther up the stream, the western slope has a covering of bowlders in variety continuous with the deposit next to be described, which covers the southern end of the 10,100-foot hill lying west of the south branch of Turkey Creek at this point.

The deposits lying near the junction of the two branches of Turkey Creek are classed as older drift because of (1) their composition, which is different from that of the Lake Fork glacial deposits to which they are adjacent; (2) their position in a narrow valley which meets the edge of the Lake Fork Glacier in an angle acute in the direction of motion of the glacier; and (3) the unglaci-

ated channel of the stream for three-fourths of a mile above the highest of the deposits.

WEST OF THE SOUTH BRANCH OF TURKEY CREEK

On the southern end of the 10,100-foot hill west of the south branch of Turkey Creek, glacial débris extends from 10,100 feet elevation down to the stream on the east. The surface here consists of arkose soil with numerous bowlders, some rounded and some angular. On the south side at about 10,000 feet elevation a bowlder of Potosi rhyolite, 18 feet in diameter, has distinct glacial striae on a part of its surface where it has been measurably protected from weathering. Other Potosi rhyolite bowlders are found, one as much as 12 feet in diameter.

About one mile east of south from this hill on a southwestward-facing slope an exposure of drift occurs at elevation about 10,100 feet; the soil here also is arkose containing bowlders in variety, a few of which are striated. This area is continuous over the top of the ridge to the northeast, down to elevation about 10,000 feet.

These deposits are classed as older drift because of (1) their topographical position, 300 feet above the edge of drift of the more recent epoch; (2) their composition, including large bowlders of Potosi rhyolite which is unknown in the more recent drift except in small fragments; and (3) the weathered character of the material as shown by the arkose soil.

DIAMOND HILL, AND OTHER ADJACENT POINTS

Deposits classed as older drift are found on Diamond Hill (Fig. 15) and on other elevated points on the mesa between Big Bear Creek and Bilk Creek, as shown on the map (see Part I). The deposits in all these places so closely resemble each other in composition and general appearance that it would be impossible to distinguish one from the other if all were transferred to one place. The one most noticeable characteristic common to all is the presence of rather irregular bowlders of Potosi rhyolite from 4 to 10 feet in diameter, the larger size being the more frequent. Besides the Potosi rhyolite, other varieties of rock commonly present are basalt, diorite, diorite-monzonite, Telluride, quartzite, feldspar porphyry,

sandstone, and shale. Many of these bowlders, even of the hard varieties such as diorite, are well rounded. It is noteworthy that San Juan bowlders are absent. Striated bowlders were found in only one of the areas mapped, that is in the area lying east-west about three-quarters of a mile north of east from Diamond Hill. The deposit on Diamond Hill ranges up to 10 or 20 feet in thickness; the thickness at other points is not easily estimated, but may reach

FIG. 15.—Diamond Hill elevation 10,100 feet. Looking northeast from elevation 9,400 feet. Glacial drift of the earlier epoch covers the northern (left-hand) end of this mesa.

50 feet for the area three-quarters of a mile north of east of Diamond Hill.

These deposits are classed as older drift because of (1) their position, in disconnected patches on points ranging up to 500 feet higher than the nearest drift of the more recent epoch; and (2) their composition, including prominent bowlders of Potosi rhyolite which is not characteristic of the more recent drift.

ALONG THE STREAM SOUTHWEST FROM BLACK FACE MOUNTAIN

In the valley of the small stream heading at 10,600 feet elevation west of south of Black Face Mountain, glacial drift is exposed at intervals up to 10,700 feet. Clearly striated bowlders occur at 10,400 feet; at 10,500 feet bowlders in variety include Potosi rhyolite, the largest about 20 feet in diameter. Above 10,700 feet no glacial drift or other signs of glaciation are found.

This deposit is classed as earlier drift partly because of its composition, including large Potosi rhyolite bowlders, but chiefly because of the lack of evidence of glaciation in the upper part of the valley.

NORTH SIDE OF EAST DOLORES RIVER

North of the terminal portion of the glaciated tract in the valley of the East Dolores, rounded and subangular bowlders in variety occur at intervals up to elevation about 10,100 feet, that is, to a height of 400 feet above the upper limit of drift of the more recent epoch. The varieties most frequently found are diorite-monzonite and Telluride, with fragments of sandstone which is here the underlying formation. No good exposures or sections occur in this area, and no striated bowlders were found. The deposit is classed as drift because of its composition and its abundance. It is classed as older drift because of its topographic position and considerably weathered surface.

EAST SIDE OF EAST DOLORES RIVER

On the east side of the East Dolores River, above the mouth of the branch heading at Lizard Head Pass, a belt about three-eighths of a mile wide above the upper limit of glaciation as mapped for the more recent epoch contains occasional deposits of bowlders in variety, and an irregular topography including at the southern end of the belt some undrained depressions. The irregularity of the topography is, in part, clearly due to landsliding, but striated bowlders found in some parts of the area are evidence that the surface deposits include glacial material. As has already been stated, this belt is classed as older drift because of its topographic position, high up on the slope, and because of the relative scarcity of the drift in this belt as compared with the deposits of the more recent epoch near the stream.

NORTH SIDE OF STREAM HEADING WEST OF GRIZZLY PEAK

On the north side of the stream, outside the limit of glaciation of the more recent epoch, and extending down the valley to elevation about 10,600 feet, rounded and subangular bowlders are mingled, with shale fragments, including Telluride up to 8 feet in diameter, monzonite, and other forms of igneous rock. This area is classed as older drift chiefly because of the striking difference in topography, as compared with the newer drift above 10,700 feet elevation. At the limit of the more recent drift as mapped, the surface of the moraine near the stream is 150 feet above the bottom of the valley with a westward-facing slope of 30° to 35°. In the older drift area outside, the hillocks are low, with flattened crests and gentle slopes.

On the south side of the stream in the area of more recent drift, moraines also occur; on the south side of the stream opposite the older drift area, as mapped, are precipitous faces of outcropping rock or slopes of talus.

AREAS BETWEEN SHEEP MOUNTAIN AND EAST DOLORES RIVER

The area west of Sheep Mountain is for the most part heavily wooded, and the surface deposits are much obscured. At two places, however, glacial deposits were found. One area is at about 10,400 feet elevation, half a mile south of the limit of glaciation, as mapped, for the more recent epoch. It consists of a short ridge extending in a northeast-southwest direction, with some irregular topography including kettles on the west, and a nearly level area to the east joining the steeper slope above. An exposure on the western side of the ridge shows the usual composition for moraines. The other area includes deposits found near the stream which heads west of Sheep Mountain. From elevation about 10,400 feet up to 11,600 feet, drift occurs nearly continuously near the stream. For about a quarter of a mile above 10,500 feet elevation on the right side of the stream is a distinct ridge with top 30 to 40 feet above the bottom of the valley; this ridge consists of typical glacial débris, including striated bowlders. On the left side of the stream opposite this moraine, and on both sides up to 11,600 feet, the glacial deposit is often merely a surface covering, showing no distinctive topography characteristic of glacial deposits. Striated bowlders were found at 11,600 feet on the left side of the stream.

Below 10,400 feet occasional accumulations of gravel and bowlders in variety occur as far as the limit as mapped for ice of the more recent epoch. Much of this débris below 10,400 feet cannot be distinguished from valley train deposits, and is therefore not included in the area of older glaciation.

So far as composition and position are concerned, the deposits in these two areas west of Sheep Mountain might be referred to glaciation of the more recent epoch. They are classed as older drift because the valleys on the western side of Sheep Mountain from which it seems they must have been derived do not present the evidences of glaciation such as are found in the other high valleys which are known to have been occupied by glacial ice in the more recent epoch. It is possible that, with the fuller examination of this area which could be made if the forests were removed, relations of the drift of these areas may be established which will result in its reference to the more recent glacial epoch.

OTHER AREAS

At numerous other points, especially on the mesas between Remine Creek and Deep Creek, and again on points and ridges north of the East Dolores River, patches of bowlders occur which closely resemble glacial drift. But either because of poor exposure of the deposit, or because no striated bowlders could be found, these areas have not been mapped. Although not recorded because the evidence is considered insufficient to warrant their classification with undoubted glacial deposits, it is nevertheless believed that in many cases they represent remnants of former moraines, or possibly in some cases outwash plains from glacial sheets of an earlier epoch.

LANDSLIDES

Although not to be classed as glacial phenomena, a brief discussion of landslides and the topography resulting from them in the quadrangle is necessary because areas occur which present at the same time some of the characteristics of areas in which the materials have come to their present position by sliding or slumping, and some of the characteristics of typical morainal deposits. In most of the works previously cited reference is made to the frequent occurrence of landslides in the San Juan region, and in one, *Pro-*

fessional Paper 67, Mr. Howe has considered their occurrence and causes at length, and has called attention to the fact[1] that under certain circumstances masses of material moved by landsliding and masses deposited as glacial moraines may resemble each other so closely as to give rise easily to errors in interpretation. As criteria in such cases Mr. Howe says that "recourse must be had to strictly geologic evidence—that is, the condition and character of the material and its relation to rock in place."

In a discussion of the same problem as presented in the Uinta Mountains, Mr. Wallace W. Atwood[2] lays especial emphasis on the value of topography and topographic relations in the determination of doubtful cases of this kind, saying that "the chief criteria used have been, first, the topography of the material; second, the topography of the basin or valley affected; and third, the topographic relations in the basin or valley."

It is of course necessary constantly to bear in mind the fact that, so far as the region under consideration is concerned, the question usually most difficult to decide is not whether a given mass of material has its present form and position as a result (1) of glacial action exclusively, or (2) of landsliding exclusively; but that it is as a rule a very different one, embracing two distinct phases, viz.: (*a*) to determine with some degree of accuracy what share each of the two classes of agencies referred to above may have had in determining a given arrangement and location of débris; and after this is done, (*b*) to decide how completely the work of each class of agencies is to be represented on a map showing the geology of the region. Or, stated briefly and in order, the points to be ascertained about such doubtful areas are:

I. Agencies involved.
   1. Glacial action to the exclusion of landsliding.
   2. Landsliding to the exclusion of glacial action.
   3. Glacial action with later landsliding.
   4. Landsliding with later glacial action.
   5. Various successions and alternations of glacial action and landsliding.

[1] *Op. cit.*, pp. 16 and 17.

[2] *Professional Paper 61, U.S. Geological Survey*, pp. 63–65.

II. In the case of (3), (4), or (5), percentage of total action represented by each of the two agencies.

III. In the case of (3), (4), or (5), is the area to be mapped as landslide or moraine?

It is to be noted in regard to the points named above that as regards I, 1, it is highly probable that in strict literalness there is no morainal deposit anywhere which has not subsequently been subject in some degree to a settling and shifting of its materials, and if the deposits have had steep slopes some of these movements would no doubt deserve the name of landsliding; the same thing must necessarily be true of morainal deposits laid down on steep slopes of underlying material of whatever nature, or on any slope which is made up of materials which are themselves creeping, slumping, or sliding; but in many cases the amount of readjustment of material has evidently been so small that the effects due to landsliding may be disregarded. As to point III above, the question of representation on an areal map may sometimes be difficult to decide. It would seem that on a general areal map that agency should be represented which has clearly had the larger share in the transportation of the material at or near the surface; this necessarily means that agency which has most recently accomplished a notable amount of transportation of materials at or near the surface. On a map drawn to show especially glacial phenomena, even a small percentage of glacial débris may properly determine the inclusion of the area within the glaciated tract. Another method combining both of the above, used on the areal sheet of the *Engineer Mountain Folio*, is at times very desirable, especially in the case of valleys where the drift is in general small in amount, viz., to indicate the upper limit of glaciation by a definite line, and within the glaciated area to map moraines, landslides, bed rock, etc., as the character of the surface in the respective cases may warrant.

On the map (see Part I) the purpose has been to show clearly the maximum extent of glaciation in the recent epoch, and consequently no account has been taken of the fact that at some points within the areas indicated the débris has been notably readjusted in position by creeping, slumping, or sliding; this is especially true

(1) of the areas indicated as landslide near Trout Lake on the areal map of the *Telluride Folio*, and (2) the tongue of the landslide area extending to the westward down the east slope of the valley of Lake Fork, 4 to 5 miles south of Keystone. As noted in the detailed descriptions of glaciated valleys, there are numerous striated bowlders in the two regions referred to, but there has also been a marked amount of slipping and readjustment of material, so that the application of the principle laid down above, namely, that the most recent agency to produce notable results should take precedence, would require the mapping of landslide areas on an areal map practically as shown in the folio. The application of the same principle results, however, in some reduction of the area referred to as the Silver Mountain landslide by Mr. Howe.[1] For, as noted in the description of the upper part of the valley of Prospect Creek, and of the area west of Turkey basin and Alta basin, the topography and materials are in both cases characteristic of glacial action rather than of landsliding for some distance within the boundary of the landslide area as mapped in the folio. It is to be said, however, that the lower limit of the glaciated area as shown on the map (see Part I) is drawn somewhat arbitrarily, since the characteristics due to glacial action as already described, and those due to landsliding, are mingled together near the boundary in a manner which makes an accurate determination of the share which each had in the movement of materials difficult, or sometimes impossible.

With respect to the time relations involved in the landsliding, reference has already been made to observations which prove conclusively that some of the movements antedated the epoch of the more recent glaciation, as for example the great block of Potosi rhyolite two and one-half miles south of east of Trout Lake (Fig. 7). The well-cleaned-out cirquelike valley head to the northeast of this block, as well as the typical ground moraine topography of the glacial drift west of Turkey basin and Alta basin, shows that, at these points at least, the amount of landsliding since the recent glacial epoch has been insignificant, even though other areas near by in each case show evidences of a considerable amount of movement since the ice withdrew.

[1] *Op. cit.*, p. 17.

ROCK STREAMS

Within the Telluride quadrangle there are in all about 20 of the peculiar accumulations of angular rock fragments to which has been given the name of rock streams or rock glaciers; the location of the most of these is shown on the map (see Part I). The characteristics of such areas have been noted by various observers in this region, although none were recorded for this quadrangle at the time the folio was published. They occur for the most part at an altitude of 11,000 feet or more above sea-level, in cirques or in the upper portion of valleys at about the elevation at which cirques occur, usually at the base of precipitous walls of rock. They extend in some cases for as much as a quarter of a mile down the somewhat flattened bottom of the cirque, and rise as much as 20 to 30 or even 40 feet above the bottom of the narrow, valley-like depressions which separate them from the slopes of talus at the base of the side walls, as in the valley of the stream tributary to Mill Creek heading west of Dallas Peak. In other cases the rock stream consists of a belt or band of rock fragments lying approximately parallel to a steep cliff face, the distance covered being less in a direction perpendicular to the cliff than in the direction parallel to it, as in the valley of Canyon Creek east of Gilpin Peak, and in Middle basin, a tributary of the valley drained by Marshall Creek. In still other cases the rock stream covers an irregular area, but is located at about that part of the valley head where snow and ice collected in the winter would evidently be likely to be largest in amount, and protected in such a way as to be likely to remain longest in the spring, as for example the small area at the head of Turkey basin (Fig. 9).

In topography the surface of these areas resembles moraines in the following respects: (1) the elevations are usually in the form of ridges, sometimes irregular in arrangement, sometimes transverse to the direction in which the mass is being moved, and sometimes parallel or subparallel to the direction of movement; (2) between these ridges are many irregular depressions, corresponding to the kettles of typical morainic topography, having dimensions up to 100 by 25 feet and usually not more than 10 to 15 feet in depth, though one exceptional area in Middle basin has a depression 50 to

60 feet in depth. As to the outer boundary of these areas, the degree of slope is often as steep as can be formed by the fragments composing it. This is true both of the sides where the rock stream extends as a tongue down the valley, and of the lower end or terminal portion. In some cases, as in the area in Turkey basin (Figs. 10 and 11), the fragments making up the outer slope were found so insecure in their position as to make climbing difficult, numerous fragments sliding and falling down the slope whenever an attempt was made to secure a foothold.

In a few cases, as for example in Middle basin, a valley tributary to the valley drained by Marshall Creek, in the upper part of the valley of the tributary of Mill Creek heading west of Dallas Peak, in Savage basin, and in Ingram basin, rock streams of at least two distinctly different ages occur. The more recent is composed of fragments fresh in appearance, angular, and bare except for lichens on some of the surfaces. In the case of the older, the rock fragments are much disintegrated, so that the crests of the ridges are less sharp, and soil enough has accumulated to support vegetation, making the surface appearance that of rounded, green hills instead of bare ridges of angular fragments. These rock streams of earlier age usually lie at the lower or outer edge of the corresponding areas of more recent date, but in at least one case, in the upper part of Savage basin just beyond the eastern boundary of the quadrangle, the stream of unweathered fragments has passed around and beyond a small area of the earlier, appearing to have been deflected in its movement as by an obstacle, but spreading out again below the obstruction after having passed it.

To account for the presence of these accumulations of rock fragments two principal causes have been assigned, namely, (1) landslides, moving "with a sudden violent rush that ended as quickly as it started," and (2) the effect of the presence of interstitial ice, cementing the fragments together, and producing with changes of temperature a movement similar to that of glaciers. The former view is advanced by Howe in *Professional Paper 67, U.S. Geological Survey*, p. 54; the latter by Capps, in the *Journal of Geology*, XVIII (May-June, 1910), 362–64. Each of these authors recognizes other possible causes, but considers such others as may

be present as of minor importance. So far as the observations made by the author of this paper in the Telluride quadrangle give a basis for conclusions, it appears that these accumulations of rock fragments are due primarily to the work of ice as indicated by Capps in the article just referred to. The reason for assigning this cause as the principal one in the case of the rock streams in this quadrangle may be summed up from the descriptions already given as follows:

1. The topography of the surface, consisting of irregularly disposed ridges and kettle-like depressions.

2. The steep slope of the outer boundary, formed of fragments insecure in position, showing that they have been but recently moved to their present place.

3. The considerable distance which much of the material has been moved from the cliff from which it has been derived.

4. The location of these areas at elevations practically the same as that at which crevassed *névé* ice was reported "on the north slope of the high ridge east of Dallas Peak."[1] When this slope was visited in August, 1905, no mass of ice was visible, but rock streams were observed both on the north slope of this ridge and over the divide east of Gilpin Peak.

5. The location of a considerable number of the rock streams in positions where snow and ice would be most likely to accumulate in large amount, and likely also to be best protected from the sun's rays. The larger areas are, of course, found in positions directly exposed to the rays of the sun, but the smaller ones are far more abundant at the foot of northward-facing, or northwestward-facing precipitous slopes.

6. The relation in position of the rock streams of two distinctly different periods of movement in which the later appear to have moved around the earlier, deploying after passing the latter as in the case of actual glacial movement.

If the interpretation here given of the above phenomena is correct, the rock streams in this quadrangle are to be considered as representing incipient glacial movement. With respect to the last period of glaciation such movements are clearly to be regarded as

[1] *Telluride Folio*, p. 15.

part of the last, feeble, intermittent struggles of the glacial forces which earlier in the epoch acted with such vigor in the same region.

SUMMARY AND CONCLUSIONS

TOPOGRAPHIC EFFECTS OF GLACIATION

1. *Cirques.*—Almost all valleys in the quadrangle which have as much as half a mile of their course above 11,000 feet in elevation were occupied by glaciers in the more recent epoch; at the heads of many of these valleys cirques were developed. A typical cirque may be considered as having (1) a nearly perpendicular bounding wall, semicircular in plan, and (2) a comparatively level bottom. In a few places this typical plan is closely approximated; in most cases, however, there is variation in many ways. The bounding wall may be only a small arc of a circle, making the resulting cirque a broadly open one; or the nearly perpendicular faces of rock may be prolonged on each side of the valley for a mile or more in the downstream direction, producing a deeply recessed valley head which approximates the linear form characteristic of valleys. The slope of the bounding wall as a rule approaches perpendicularity only at some distance above its base—usually not more than the upper one-half of the vertical height of the wall shows the steep faces left by falling blocks or fragments (Fig. 9); at the base in almost all cases are slopes of waste, generally in the form of bare rock fragments, but occasionally so far weathered as to furnish a soil where an Alpine flora can gain sufficient foothold to cover the surface in the summer months with a carpet of green. The bottoms of the cirques also present variations. In some cases much of the floor is rock in place, frequently grooved and striated, and containing depressions in its surface in which are shallow lakes varying in size up to one-fourth of a mile or more in diameter. In other cases the floor is covered in whole or in great part with rock fragments and soil; the bottoms of such cirques are as a rule more irregular and less nearly horizontal than in the case of the cirques which contain lakes. Rock streams, already described, are found only in cirques or in the upper parts of valleys at a corresponding elevation.

2. *Hanging valleys.*—Numerous hanging valleys occur in the quadrangle; in most cases they were themselves occupied by

glaciers; in all cases the valleys to which they are tributary were glaciated. As to mode of formation, the hanging valleys in this quadrangle may be divided into two classes, viz.: (1) those due primarily to glacial deposition; (2) those due primarily to glacial erosion.

The valley of Prospect Creek is an example of class (1). The lower course of this stream was covered by glacial ice moving down the valley of the San Miguel River to which it is tributary, and the morainal deposits left by that glacier across the course of Prospect Creek have been eroded only in part by the stream, leaving the bottom of its valley just outside the moraine still about 350 feet above the level of the San Miguel River. Deertrail basin is an example of class (2). The bottom of this valley is about 1,500 feet above the level of the valley of the San Miguel River to which it is tributary. There is no means of determining just how much of the valley of the San Miguel was lowered by glacial erosion at this point, but from an examination of other tributaries near, it does not seem probable that it could have been more than a very small part of the 1,500 feet mentioned above. That the San Miguel valley was much less flat-bottomed in pre-glacial time than now hardly admits of question; the present steepness of the valley wall at the point where the stream from Deertrail basin enters must therefore be due primarily to lateral erosion by glacial ice. As has been pointed out by Russell,[1] this widening of a valley at the bottom is entirely sufficient to produce the phenomena of hanging valleys in the case of tributaries with a steep gradient. The very small size of Deertrail basin, however, together with the fact that the lower end of the basin is approximately at the same level as was the surface of the ice in the valley of the San Miguel River, indicates that the conditions of glacial erosion primarily responsible for making this basin a hanging valley are those stated by Russell for mountain-side glaciers,[2] viz., a gully or other depression occupied by a small glacier whose downward limit of erosion was a distance above the bottom of the main valley equal to the thickness of the ice in the main valley less the thickness of ice in the tributary.

[1] *Bulletin of the Geological Society of America,* XVI, 80.

[2] *Ibid.*

In this connection it should be noted that not all the valleys tributary to valleys which were occupied by glaciers are hanging valleys. For a given stream it may occur that part of the tributaries occupy hanging valleys, while a part are in topographic adjustment with the main stream. For example, east of the city of Telluride the San Miguel River receives tributaries from glaciated valleys as follows: Bear Creek, Deertrail Creek, Bridal Veil Creek, Ingram Creek, and Marshall Creek. Of these, Deertrail basin, Bridal Veil basin, and Ingram basin are hanging valleys, while Bear Creek valley and Marshall basin cannot be so classed. Of the two larger tributaries from the south, Bridal Veil Creek enters the cirquelike head of the San Miguel valley by a sheer fall of 350 feet and with a steep grade below for another 500 feet of fall before it reaches the more level part of the bottom of the valley; while Bear Creek, two miles farther west, draining a glaciated area less than that of Bridal Veil basin, enters the San Miguel River by a grade no steeper than is usual for mountain streams. Other things being equal, it would seem that a valley draining a small area would be deepened less by glacial action than one draining a larger area; and if so, then the smaller valley would be more likely to be left as a hanging valley. However, Bear Creek valley, the smaller one in this instance, is not a hanging valley, while Bridal Veil basin, the larger one, is; some modifying conditions have therefore evidently been present.

A modifying condition in this case may be (1) the difference in kind of rock forming the bottoms of the valleys. In Bridal Veil basin the San Juan formation is the underlying rock, while in the larger part of the valley of Bear Creek the more easily eroded sedimentary rocks of the Jura-Trias period outcrop in the bottom for two miles or more. Or the modifying condition may be conceived to be (2) a difference in the pre-glacial topography. If the grade of Bear Creek in pre-glacial time was not steep in its lower course, and if the downward cutting of the ice in the San Miguel valley was but little different in rate from that in Bear Creek valley, a hanging valley would not be formed. And on the other hand, a steep gradient in Bridal Veil Creek in pre-glacial time would, according to the principles already referred to in the case of Deertrail

basin, be sufficient to account for the lack of topographic adjustment as seen today. A complete explanation of the present difference between these two valleys must, without doubt, include both of the modifying conditions (1) and (2), just named.

In the case of Marshall Creek, only the second of these two modifying conditions can apply. This stream enters the San Miguel valley from the north at a somewhat steeper grade than does Bear Creek from the south, yet there is no abrupt change to a steep grade in its lower course such as is characteristic of streams in hanging valleys. Comparing again with Bridal Veil basin, the area drained by Marshall Creek is considerably less, so that so far as wear of channel due to ice alone is concerned it would seem that the valley of Marshall Creek would have been lowered by a less amount than was the valley of Bridal Veil Creek. The rock exposed in the bottoms of the two valleys is in this case the same, so that the only other modifying condition which appears to be sufficient to explain the difference seen today is that of the pre-glacial topography. That is, a gradient in pre-glacial time considerably less steep for Marshall Creek than in the case of Bridal Veil Creek or Ingram Creek is sufficient to cause the present difference. If this conclusion in the case of Marshall Creek be correct, it would seem probable that the modifying influence of pre-glacial topography predominated also in the case of Bear Creek, aided in a subordinate way by the presence of sedimentary instead of igneous rocks in the lower part of its course.

3. *Rounded topographic forms.*—Topographic forms rounded in outline due to glacial action, in contrast with the angular outlines usually found in unglaciated, mountainous areas, occur at many points in the quadrangle; they may be grouped as to origin in two classes, namely, (1) those due primarily to glacial erosion; and (2) those due primarily to glacial deposition. Class (1) includes (*a*) rounded, projecting points or masses of rock in place of which *roches moutonnées* are the type; and (*b*) valleys having a U-shaped cross-section as opposed to the sharper V-shaped section characteristic of unglaciated mountain valleys of steep grade. Class (2) consists of morainal deposits of various kinds, forming low, round-topped hills or ridges; sometimes these hills are in the bottoms of

valleys, as in the valley of the San Miguel River near Keystone (Fig. 4); sometimes they are on the tops of mesas 1,000 to 1,200 feet above the bottoms of the adjacent valleys, as on the mesa lying between Bilk Creek and Lake Fork.

4. *Silted-up lakes and ponds.*—Nearly level areas due to the silting-up of ponds or lakes occur at several points in glaciated valleys. The largest of these areas is in the valley of the San Miguel River (Fig. 3); it has a length of nearly five miles and a width of about half a mile. For the greater part of its course through this area the San Miguel River has a grade averaging about 30 feet per mile. In some parts of its course the grade is much less than this and the stream flows in wide meanders. At one point the generally level surface of this lacustrine plain is somewhat broken by low morainal hills; in other places it has been slightly modified by the accumulation of material in post-glacial time in the form of alluvial fans, a kind of modification to which practically all similar areas in the quadrangle are subject.

5. *Terraces and valley trains.*—Beyond the termini of the various glaciers, drift in the form of stratified deposits is usually found at intervals along the sides of the valleys, sometimes evident as narrow terraces or remnants of terraces. In the case of the San Miguel River these deposits extend beyond the boundary of the quadrangle, and are found at elevations up to 100 feet above the stream. The amount of débris left as valley trains is slight owing to the narrow, steep-sided valleys in which the streams flow.

CHARACTERISTICS OF THE DEPOSITS OF DRIFT OF THE EARLIER AND THE LATER EPOCHS

The drift deposits of the earlier and the later epochs are alike in being made up of a heterogeneous mixture of rounded and sub-angular rock fragments of various kinds and various sizes, including some bowlders and pebbles with striations.

The most important differences are with respect to (1) the kinds of rock present, (2) the topographic position of the deposits, and (3) the amount of erosion which has taken place since the withdrawal of the ice sheets to which the deposits of the two epochs, respectively, owe their origin. As to composition the drift of the

earlier epoch or epochs is characterized by bowlders of Potosi rhyolite up to 18 feet in diameter; that of the more recent epoch by bowlders of diorite-monzonite up to 4 feet in diameter, or of the San Juan formation up to 15 feet or more. Striated bowlders are, in general, rare in the earlier drift; in the more recent drift they are of common occurrence, and locally are abundant. As to topographic position, the deposits of earlier age occur in the majority of cases on the tops of mesas or ridges ranging up to 500 feet or more above the upper limit of the adjacent deposits of the more recent epoch. Some of the earlier drift, however, lies on slopes and in valleys in contact with the upper limit of drift of the more recent epoch just as if the earlier drift sheet had been in part overridden by the more recent glaciers. Not only does the older drift usually lie at a higher elevation than the more recent, but it also lies outside the drift boundary of the latter. In one case the earlier drift is found in a valley in which the more recent drift is not represented; in other cases the older drift lies at distances ranging up to one and one-half miles beyond the edge of the more recent deposits.

The difference in the amount of erosion to which the drift of the two epochs has been subject is shown both by the general field relations and by the topography of the deposits. The earlier drift deposits constitute in quantity a comparatively insignificant amount of material, distributed in isolated, small patches, at not less than twenty-five different places in the quadrangle. The more recent deposits, on the other hand, include prominent moraines and drift sheets which are in general continuous for each valley or drainage basin in which they occur. In topography, the earlier drift is characterized by a surface of greater regularity and smoothness, and by an absence of undrained depressions; the more recent drift, on the other hand, in a number of places shows a much more irregular surface with numerous kettle holes.

EXTENT OF GLACIATION

1. *In the more recent epoch.*—The number of glaciers occupying valleys in this quadrangle in the more recent epoch can be stated only in terms of number of terminal areas, and number of areas in which movement of ice originated. It must be remembered,

however, that this method of statement does not present complete information as to the number of glaciers which existed, for on each side of the quadrangle glaciers moved to undetermined termini beyond its borders; and on two sides glaciers moved into the quadrangle from points of origin outside. Within the quadrangle, however, there are between 80 and 90 points of origin, the exact number reckoned depending upon how many of the smaller tributaries of a given valley are considered as independent areas of initial movement. Of termini there are 14.

The total area glaciated in the more recent epoch is estimated at near 150 square miles. The greatest length of glacier lying wholly within the quadrangle, measured from terminus to most remote point of origin, is $15\frac{1}{2}$ miles. Some of the glacial ice within this quadrangle, however, was tributary to the great Animas Glacier which is reported by Mr. George H. Stone[1] to have been 60 miles or more in length.

The maximum thickness of ice was probably something in excess of 1,500 feet. The slope of the surface of the ice varied from probably 1,000 feet per mile in the upper part of small valleys to 200 feet per mile or less in the lower part of the course of the larger glaciers.

The amount of glacial erosion cannot be estimated accurately from the deposits which are found, owing to the fact that much of the débris must have been carried away by the swift streams. But even when allowance is made for the disappearance of a considerable amount, it would seem that the whole amount removed by the ice was not in excess of 100 to 200 feet in average thickness for the glaciated tract; the maximum amount of erosion may, in places, have reached 400 to 500 feet.

As already stated in the description of the drift in the valley of the San Miguel River, the deposits near Keystone may be as much as 400 feet in thickness; this depth of drift is, however, very unusual for this quadrangle. Outside of the Keystone deposits the thickest are probably those found on the mesa between Bilk Creek and Lake Fork. The maximum height here of the top of the morainal hills or ridges above the bottom of the adjacent

[1] *Jour. Geol.*, I, 471 ff.

valleys is about 1,200 feet. This is not, however, a measure of the thickness of the glacial deposits, but is an indication of about the maximum thickness reached by the glacier at the point in question. The morainal deposits cannot exceed from 200 to 300 feet in thickness, and may be considerably less. The greater part of the total elevation of the top of the morainal hills above the bottom of the valley is due to the underlying rock in place which constitutes the walls of the canyon-like valley down which the glacier moved.

2. *In the earlier epoch or epochs.*—The occurrence of the older drift at and beyond the edge of the more recent drift is conclusive proof that the earlier glaciers covered a greater area than the more recent ones. With the exception of a few square miles in the northwestern part and possibly also in the southwestern part the entire area of the quadrangle must have been affected by glaciers in the earlier epoch. The appearance of the surface for a considerable length of time in that epoch must, therefore, have been that of snow and ice, except as it was broken here and there by projecting tops of peaks and ridges on whose steep slopes the snows could find no resting-place. In view of the great extent of the glaciers of the earlier epoch, and the large size of the bowlders which constitute a part of their deposits, glacial action in that period must have been sufficiently vigorous and long continued to produce important modifications in the topography. The details of such changes, however, can never be known; we can only be sure that the glaciers of that period played no small part in the general process of degradation which is still going on in the region. The isolated patches of earlier drift which are seen today are believed to be remnants of the moraines of that early period; those moraines must have retarded the erosion of the formations on which they were deposited, and so the elevation of the mesas and ridges on which these patches of drift occur must be somewhat greater than it would have been except for the protection thus afforded. Without doubt, therefore, some of the hills and ridges in the quadrangle owe part of their present elevation and some details of their configuration to the work of glaciers in the earlier epoch; but there are no means at hand by which to determine even approximately the amount of modification due to this cause.

AGE OF THE DRIFT

1. *More recent epoch.*—The age of the more recent deposits of drift is to be regarded as the same, in general, as that of the deposits of the Late Wisconsin stage of the continental ice sheet which covered the northern part of North America in Pleistocene time. It is evident, however, that the ice persisted in the upper parts of valleys until within very recent time, as shown by the crevassed *névé* ice reported a few years ago from the northern part of the quadrangle,[1] and by the signs of recent glacial movement seen in the rock streams, previously described in this paper. While correlated with the Wisconsin stage of the continental glacier, it is for the reasons just given to be understood that glacial ice remained in the quadrangle for a very considerable period after the continental ice sheet had disappeared from the northern part of the United States east of the Mississippi River.

2. *Earlier epoch or epochs.*—In considering the age of the earlier drift deposits it is to be observed that the drift referred to an earlier epoch or to earlier epochs of glaciation may be grouped as to position in two classes, viz.: (1) that found frequently on the tops of mesas or ridges, sometimes on slopes, at elevations ranging up to 500 feet above the upper limit of the nearest glacial deposits of the more recent epoch, and at distances ranging up to one and one-half miles beyond the edge of the more recent deposits; and (2) that found in valleys whose upper portions lack the usual evidences of recent glaciation.

It is to be understood that in grouping together certain deposits under the common name of earlier drift, no assertion is made as to the age of the respective deposits with reference to each other. From a consideration of the position of the two classes of deposits named above, however, the inference is clear that the amount of erosion since (1) was deposited has been very great, while the amount of erosion since (2) was deposited is comparatively small. It is, therefore, certain that all of the deposits classed as earlier drift are not of the same age. But the evidence afforded by deposits in the Telluride quadrangle is not sufficient to warrant the conclusion that three distinct glacial epochs are to be recognized. It

[1] Cross, *Telluride Folio,* p. 15.

may prove true that the deposits classed as (2) above should be regarded as merely early phases of the more recent epoch; but additional evidence from adjacent territory is needed before the matter can be placed beyond question.

The age of the oldest of the earlier drift as indicated by the amount of erosion which has taken place since the deposit was made is probably best shown on the mesa on which Diamond Hill is located. The vertical range of the earlier drift in this area is from 9,300 to 10,100 feet in elevation; the pre-glacial surface of the mesa must, therefore, have had a relief of about 800 feet; for the underlying rocks are here chiefly sandstones or igneous rocks, so that any considerable lowering of the surface due to solution as might have been the case in a limestone region cannot have occurred. Between areas of drift now at approximately the same elevation, valleys half a mile broad and 100 to 150 feet deep exist. The slopes of these valleys are gentle, the tops of the hills and ridges rounded or flattened, and undrained depressions are practically unknown. When it is remembered that most of the valleys separating the isolated patches of earlier drift are occupied by temporary streams only, and that for a considerable period the climate of the region has been semiarid, it is evident that the time represented by post-glacial erosion on this mesa is very long.

In considering the relation of the oldest of the earlier drift to that of the more recent epoch, one feature seemed especially prominent as the fieldwork was in progress; that is, the presence of large San Juan bowlders as the most conspicuous constituent of the more recent drift from the main valley of the San Miguel, and similarly, equally large Potosi rhyolite bowlders, characteristic of the oldest of the earlier drift on the mesas and ridges adjacent to the same stream. The presence of large bowlders of a given formation in abundance in drift of a certain period at once raises questions as to the conditions under which glaciers get possession of an abundance of large rock fragments. Judging from the composition of the drift brought down the main valley of the San Miguel to Keystone, and from the relation of the exposures of the various formations in the upper valleys tributary to the San Miguel, it would seem that an abundance of large bowlders in drift is to be

considered as an indication of "plucking" in the bottom of glaciated valleys. It is conceivable that the process of sapping might result in large blocks of rock outcropping above the surface of the ice to fall and be carried on the surface; and there can be no doubt that this sometimes occurs. But in the case of the cirques tributary to the San Miguel River, the summit of their bounding walls consists of an almost continuous ridge of Potosi rhyolite ranging up to about 1,000 feet in vertical extent, 500 feet or more of which was probably all the time above the surface of the glaciers filling the cirques. Yet in the drift left by the ice from these valleys, the Potosi rhyolite is indistinguishable except in small fragments. On the other hand, the San Juan formation, which occurs in the drift in abundance in bowlders up to 18 feet in diameter, outcrops in the lower part of the cirque valleys from 10,000 to 12,000 feet in elevation, and presents in many places the precipitous walls in the bottoms of the valleys transverse to the streams which have been referred to as giving to these valleys a roughened, unglaciated appearance when viewed from below. The appearance of the faces of these cliffs transverse to the valleys is such as would result if the rock were plucked off in large masses. If sapping had any considerable share in supplying the large bowlders of the San Juan formation found near Keystone, it must have occurred at the points where valleys such as Bridal Veil Creek and Marshall Creek join the San Miguel. Here the San Juan formation was exposed in precipitous walls 1,500 to 2,000 feet above the surface reached by the ice. There is no evidence, however, that lateral erosion at these points was sufficient to amount to undercutting; the walls are precipitous but not roughened as if by the removal of large blocks, and the débris which is now falling is for the most part small fragments.

The other drift deposits of the more recent epoch are not characterized by large bowlders. Drift brought by the Lake Fork Glacier is characterized by diorite-monzonite bowlders rarely over 3 or 4 feet in diameter. This formation outcrops in the bottom and sides of the valley in the neighborhood of Ophir Station where precipitous plucked faces occur. Here also the upper slopes of the sides of the valley above the elevation reached by the surface of the

ice may be considered as possible sources of fragments; but they present no evidence of undercutting or of sapping.

It will require much more extended observation to determine without question what the precise relation may be between the average elevation of an area of glaciation and the horizon of a formation prominently represented in the drift by large fragments. But the evidence, as far as observations in the valleys of this quadrangle are concerned, points to the conclusion that an abundance of large bowlders of a certain formation in the drift from a given glaciated area indicates an outcrop of the formation in the bottom and sides of the middle and lower parts of the high valleys in which the glaciers in question were formed. As the San Juan formation lies at approximately 10,500 to 12,000 feet in elevation for its lower and upper limits, respectively, and as the Potosi rhyolite has its lower limit at about 12,500 feet elevation, we should have, on the basis of the foregoing conclusion, a position of the middle part of high glaciated valleys in the earlier drift epoch of not less than 1,000 feet above the level of the present cirque valleys. Or, in other words, that sufficient time has elapsed since the period of the earlier glaciation in this region to permit the removal by erosion in the high mountain tracts of not less than 1,000 feet of igneous rock. This interval of time manifestly must include (1) an interglacial interval, which presumably was of long duration, and (2) the period of more recent glaciation.

POST-GLACIAL CHANGES

The changes due to agencies acting in post-glacial time are chiefly the formation of alluvial cones and fans, alluvial and lacustrine deposits along streams and in lakes or ponds, and talus slopes, and in the renewal of the process of downward cutting by streams in nearly all the valleys. Of the deposits named, the accumulations of talus are largest in amount, slopes of talus 1,000 feet or more in length occurring in a few places. But the total amount of all the post-glacial deposits is insignificant; they are, in general, recognizable only at the base of cliffs or steep slopes and at certain places in the bottoms of valleys. The amount of post-glacial erosion is also in all cases relatively very small; the materials of the drift

generally present a fresh, unweathered appearance; undrained depressions in morainal tracts are still numerous; and streams have cut channels in bed rock not more than 10 to 20 feet in depth in the more favorable locations.

GLACIATION AS AFFECTING THE LOCATION OF MINING CLAIMS

It is reported that the first prospectors in this region found some exceptionally large fragments of ore-bearing rock on the lower slopes of valleys now known to have been glaciated; small fragments are still occasionally met with. In a few cases it seems that these fragments have been taken to be an indication of an outcrop of a vein near by, and considerable effort has been expended in driving tunnels into the underlying bed rock in search of the ore body from which the fragments came. It should be remembered, however, that if fragments of ore-bearing rock are found on the surface within the area shown to have been glaciated, they have little value as indicating that the parent vein or ledge is near at hand. This is particularly true of those parts of valleys in which moraines are found; fragments found in the upper parts of valleys which are comparatively free from débris are more likely to be but a short distance from the outcrop of the body of ore. But the general rule is nevertheless in all cases to be recognized, that fragments found on the surface in any part of a glaciated area may have been derived from a ledge close at hand, or may have been brought from any point in any part of the valley above.

ON THE STRATIGRAPHIC POSITION AND AGE OF THE JUDITH RIVER FORMATION

A. C. PEALE

PART III

THE PALEOBOTANICAL EVIDENCE

We have as yet no fully diagnostic flora for the Judith River beds, the plants from them being few in number and confined to two localities, one of which is in reality not positively placed stratigraphically. This meager collection, therefore, is by itself inconclusive. That fossil plants will be found later on is undoubtedly true, as indications of their presence have been noted, but they are evidently not abundant in the formation, careful search on our flying trip having proved entirely unsuccessful. In this connection it may be said that plant remains are similarly infrequent also in the Lance formation and in the Edmonton or "Lower Laramie" of the Canadians. The plants described from Willow Creek by Knowlton[1] from the beds referred to the Judith River by Stanton and Hatcher[2] are undoubtedly of Belly River age and do *not* come from the Judith River formation.

In 1908 fossil plants were collected by members of the U.S. Geological Survey from beds supposed by them to be of Judith River age near the Macklin Coal Company's mine on the Big Sandy in Montana. This locality is about 12 miles northeast of the Big Bend of the Missouri River below Fort Benton, and between 30 and 35 miles northwest of Judith Landing on the Missouri River near the east end of the Bearpaw Mountains. The list of plants as identified by Dr. Knowlton is as follows:

Viburnum perplexum Ward.
Plantanus nobilis Newberry.
Populus sp. (large leaf).

[1] *Bull. U.S. Geol. Surv., No. 257*, pp. 129–55.

[2] *Ibid.*, pp. 56–58.

Populus cuneata Newberry.
Populus glandulifera Heer.
Berchemia multinervis Al. Br.
Viburnum sp.
Sapindus grandifolius Ward.
Taxodium distichum miocenum Heer.

These are of undoubted Fort Union age, but as the named species are common to both the Upper and Lower Fort Union (Lance) formations, it is impossible, without knowing the exact stratigraphic relations, to say which of the two they represent. The probabilities are that they are from the Lower and are, therefore, from the Lance, that is, that they are really from the Judith River (not Belly River) beds, in accordance with the belief of the collectors; and they are likely to have come from the upper part of this series. However, at the present time it is impossible to make any very positive statement regarding them.

The second locality is on Cow Creek, where Dr. Stanton found many leaves of *Trapa(?) microphylla* about 30 feet above the base of the Judith River beds. This species has a wide distribution in the Fort Union formation, occurring in both the Upper and the Lower Fort Union beds, having been found abundantly by Professor L. F. Ward at Burns ranch on the Yellowstone below Glendive and at many other localities and by other collectors in the Lance formation in Converse County, Wyo. It is also found in the Canadian "Lower Laramie" which, as we regard it, is the equivalent of the Lance formation and of the Judith River beds. The type of *Trapa(?) microphylla* was described by Lesquerreux from the Montana formation of Point of Rocks, but, as Knowlton[1] has indicated, it is questionable whether the species from the Montana and from the Fort Union and underlying beds are all one and the same.

In regard to the plants of the Lower Laramie (or Judith River series in Canada), concerning which Dawson[2] made the statement that "the flora of the Belly River closely resembles that of the Lower Laramie," it is to be urged that comparison of the two lists shows that the resemblance between the floras is, after all, not very

[1] *Bull. U.S. Geol. Surv., No. 163,* 1900, p. 63; *ibid., No. 257,* 1905, p. 145.

[2] *Trans. Roy. Soc. Canada,* III, sec. IV (1885), p. 20.

striking. Besides, as Dawson[1] himself adds, "the few species are scarcely sufficient to afford a basis for definite conclusions." The list for the lower division of Dawson's Laramie contains eight species, of which six are common to both Upper and Lower. Two of the species, *Onoclea sensibilis* and *Sapindus affinis*, are characteristic of the Fort Union in both of its divisions on the American side of the line. As to the Belly River list, it does not seem to be complete, *Pistia corrugata*, a characteristic Montana flora not being included. Adding this to the list, we have ten species, two of which, according to Knowlton, should be dropped. Only two of those remaining seem to be common to both Belly River and Lower Laramie, and this small proportion certainly cannot be said to establish a striking resemblance between the two floras. Regarding the others, Knowlton says:[2]

> As to the affinities of the other named species, it may be mentioned that *Nelumbo dawsoni* is very closely allied to my *N. intermedia* from Point of Rocks, Wyo., while the other two species (*Populus latidentata* and *Acer saskatchewanse*) are not figured, nor are they described with sufficient fullness to permit of satisfactory comparison with other forms.

Stanton[3] was probably correct when he said:

> I suspect that in Canada two distinct formations, separated by marine beds, have been confused under the term Belly River series, and that a large part of the fauna, and possibly also of the flora, was collected from the upper horizon, which included the Laramie and possibly even later beds.

It seems equally true that in this country the same formations have been confused. Our knowledge of the flora, of the Lance formation, has been considerably enlarged in the past few years.[4] The Belly River flora, however, is in need of critical study, and until that can be done we must content ourselves with the confident prediction that the difference between them will be greater than now appears; and that when a flora for the Judith River beds is developed, its affinities will be with the Lance rather than with the Belly River flora indicated above.

[1] *Trans. Roy. Soc. Canada*, IV, sec. IV (1883), pp. 32, 33.

[2] *Bull. U.S. Geol. Surv., No. 257*, 1905, p. 154; see also *ibid., No. 163*, 1900, pp. 9, 10.

[3] *Ibid., No. 163*, 1900, p. 11.

[4] See Knowlton *Proc. Wash. Acad. Sci.*, XI (1909), 179–238.

THE INVERTEBRATE EVIDENCE

According to Dr. T. W. Stanton:[1] "As the Judith River is essentially a non-marine formation, strictly speaking its fauna should not be made to include the marine species" which in the one occurrence noted by him, he supposes to have been "brought into the Judith River area by a local temporary invasion of pure marine waters." There is also in the formation "a brackish-water fauna of wide geographic distribution confined to thin beds in its upper and lower portions of the formation."

It is apparently the consensus of opinion among invertebrate paleontologists that fresh-water faunas *per se* are of little or no value in the accurate determination of the age of beds in which they occur. Fresh-water beds are found at a number of horizons between the Devonian and the present time. In the Devonian, shells resembling the modern Unio have been found and Unios of similar types have also been collected from the Triassic and Jurassic. Writing of the fresh-water beds at the top of the Jurassic Dr. Stanton[2] says:

> Its invertebrate fauna consists of several species of *Unio*, *Vivipara*, *Planorbis*, etc., all of modern fresh-water types, which do not assist in discriminating between Jurassic and Cretaceous. Unios have been found in several horizons in the Cretaceous, and when we get as high as the Ceratops beds (Lance formation) many, if not all of the specific types found there, may be found also among living species.

Whitfield[3] describing the Unios from the Hell Creek region of Montana says of fourteen species that they are "so nearly like the living species that it would do but little violence to specific features to say they were the same."

Writing of the non-marine faunas found in the Ceratops beds of Converse County, Wyo., Stanton says:[4]

> It must be admitted that in themselves, without any reference to stratigraphic occurrence or local geologic history, these fossils could not be depended

[1] *Bull. U.S. Geol. Surv., No. 257*, pp. 119 f.

[2] *Jour. Geol.*, XVII (1909), 414.

[3] *Bull. Amer. Mus. Nat. Hist.*, XXIII (1907), 624.

[4] "The Age and Stratigraphic Relations of the 'Ceratops Beds' of Wyoming and Montana," *Proc. Wash. Acad. Sci.*, XI (1909), 288.

upon for the discrimination of horizons within the Cretaceous nor for distinguishing between Cretaceous and Tertiary.

Fresh-water invertebrates therefore cannot be depended upon as time-markers in geologic investigations; still it is true as Stanton further says:[1]

> When the investigation is confined to a single region and when the geographic and stratigraphic range of non-marine species has been determined their evidence is useful and important.

Therefore, from the viewpoint of the present writer the stratigraphic position of the Judith River beds is the same as that of the Lance formation, or the lower portion of it; a comparison of their fresh-water faunas is interesting and instructive, because it corroborates to a considerable extent the more conclusive evidence presented by the vertebrates.[2]

THE VERTEBRATE EVIDENCE

Hayden in his early explorations in 1855 collected in the Judith River basin, not only marine invertebrates from the Fox Hills sandstones underlying the fresh-water fossiliferous Judith River beds, but also obtained from the latter, vertebrate remains which constitute the first horned dinosaurs of the *Ceratopsia* ever collected in this country. These, and other specimens from near Long Lake, N. D., in what is now called the Lance formation, were studied by Dr. Joseph Leidy, resulting in the establishment by him of four genera and species of dinosaurs.[3] Later, his descriptions were elaborated and published[4] with illustrations. Although in his first article, Leidy thought that the Judith River formation might be of Wealden age, in his second publication he was inclined to consider the formation as "a part of the great Cretaceous series of Nebraska, though [he says] we should not feel surprised if future explorations should determine it to be of Tertiary age."[5] In the

[1] *Proc. Wash. Acad. Sci.*, XI (1909), 285.

[2] Stanton, *op. cit.*, p. 286, refers to the widespread association of some of the species in association with the dinosaur fauna, stating that a "large proportion of them, including some of the more striking and characteristic forms, occur at Black Buttes."

[3] *Proc. Acad. Nat. Sci., Phila.*, VIII (1856), 72–73.

[4] *Trans. Amer. Phil. Soc.*, XI, N.S., Philadelphia, 1860, pp. 138–54.

[5] *Ibid.*, p. 140.

opinion of the writer this prophecy of Leidy's made in 1860 is today being verified.

Professor E. D. Cope, with the assistance of C. H. Sternberg and John C. Isaacs, spent a part of the summer of 1876 in the exploration of the Judith River basin between Fort Benton and Armell's Creek, 130 to 150 miles farther down the Missouri River,[1] and secured a considerable number of dinosaurs, referable to several new genera and species, and fragmentary remains afterward determined to be *Ceratopsia*. Hatcher spent a couple of months of the summer of 1888 in the Judith River badlands with what he calls very indifferent success,[2] and in the summer of 1903, with T. W. Stanton, spent two more months "in the field study of the Judith River and associated formations of northern and central Montana and adjacent areas of Canada."[3]

In the interval between 1855 and the present time (1912) explorations have been carried on over widely separated areas in the Rocky Mountain region of the United States, resulting in the discovery and development of many localities from which vertebrate remains (many in a fragmentary condition) have been collected, the beds in which they occurred being post-Laramie formations. The most characteristic species appear to be those of genera belonging to the *Ceratopsia*, one of the first described species coming from the beds at Black Buttes, Wyo.

Besides the localities in Converse County, Wyo., collected by Hatcher, Williston, Baur, and Case, and the Denver and Arapahoe areas of Colorado by Cannon, Cross, and Eldridge, and the Hell Creek region by Barnum Brown, many others in the Rocky Mountain region have yielded vertebrate remains, mostly, however, in a fragmentary condition. Thus *Ceratopsia* have been found near the North Platte River in Wyoming about 40 miles north of Fort Steele by Hatcher in 1888, and from near the same locality by Knowlton and Peale in 1910, here also by Hatcher, on the east side of the Big Horn Mountains 40 miles south of Buffalo, Wyo.; on the west side of the Big Horn River between Fort Custer and Custer Sta-

[1] *Bull. U.S. Geol. and Geog. Surv. Terr.*, III (1877), 565–97.

[2] *Monograph U.S. Geol. Surv.*, XLIX (1907), 7.

[3] *Bull. U.S. Geol. Surv., No. 257*, 1905, p. 9.

tion, Mont.; and north of Musselshell, Mont. In addition to the Hell Creek specimens listed by Barnum Brown he collected *Triceratops* and *trachodont dinosaurs* south and southeast of the Yellowstone River in Montana, Wyoming, and the Dakotas. Throughout this general area also the various parties of the U.S. Geological Survey engaged in tracing the distribution of the coal formations during the past six years have brought in numerous vertebrate specimens of similar character, showing their wide distribution in the Lance formation.

As noted on a preceding page, Hayden was unable to detect any material difference between the deposits of the Judith basin and those of the Fort Union, especially of the portion lying at the base of the latter in the Missouri River region extending to the eastward. Similarly all the earlier paleontological workers could not make any separation based on the vertebrate remains found in them and did not separate the Judith River beds faunally from the beds, that, at Long Lake, N.D., and along the Yellowstone River and several other localities, lie immediately below the undisputed Fort Union. Cope also in his work in northeastern Colorado recognized that he was dealing there with beds identical with those of the upper Missouri River country, especially the reptile-bearing portion of the Fort Union.[1] As the area of exploration in the west widened, and collections, fragmentary as most of them were, increased, and admittedly insufficient and fragmentary as is the material from the Judith River basin, the more evident became the remarkable resemblance between the faunas from the beds now referred to the Lance formation and those of the Judith River beds. Undoubtedly this would have been still more evident had there not been a strong effort to differentiate them, due to a misapprehension as to the supposedly vastly older age of the Judith beds as deduced from supposed stratigraphic evidence. The probability of the Judith River beds being of post-Laramie age on account of the stratigraphic position and the contained vertebrate remains is referred to by Cross.[2]

[1] *U.S. Geol. and Geog. Surv. of Terr. for 1873, 1874,* pp. 429, 430.

[2] *Monograph U.S. Geol. Surv.,* XXVII, 239.

Williston[1] notes a "startling resemblance" between the Wyoming Laramie [Lance Creek] fauna and that of the Judith River and Belly River series. Of course, if they are equivalent to each other, as we claim, this resemblance is not so startling. Williston, however, is not alone in mentioning this resemblance. Hatcher[2] himself says:

When considered in its entirety, the vertebrate fauna of these beds [Judith River beds] is remarkably similar to, although distinctly more primitive than, that of the Laramie [Lance formation]. Almost or quite all of the Laramie [Lance formation] types of vertebrates are present, though as a rule they are represented by smaller and more primitive forms.

However, it remained for Dr. O. P. Hay[3] fully to bring out this resemblance and demonstrate the equivalence of the Judith River and Lance formations. Having demonstrated, as he supposes, that there was a nearly complete change in the fauna and a considerable change in the flora between the time of the deposition of the Lance Creek beds and those known as Puerco and Fort Union, he says:

I will endeavor to show that the fauna of the former beds is closely related to that of the Judith River. This close relationship of the two faunas has been recognized, it may be truthfully said, by all paleontologists who have given attention to the subject.

In his discussion of the relationship of the two faunas Dr. Hay begins with the fishes and follows with the tailed amphibians. He quotes Hatcher, who says eight species of fishes have been described from the Judith River deposits. Of these Hatcher says:

While they give an indication of the character of some of the fishes that inhabited the waters of this region in Judith River times, they are at present known from such insufficient material as to render them of little value for purposes of correlation, as is abundantly evidenced by the apparent similarity existing between the fish remains known from these beds and those from the Laramie [Lance formation]. This similarity is so striking that some paleontologists have been led largely from such evidence to *correlate the Judith River*

[1] *Science*, N.S., XVI (1902), 952.

[2] *Bull. U.S. Geol. Surv., No. 257*, 1905, p. 107.

[3] Reprint from the *Proc. Ind. Acad. Sci.*, Twenty-fifth Anniversary Meeting, 1909, pp. 1–27.

beds with the Laramie [Lance], *disregarding the more important evidence afforded by the dinosaurian fauna and the stratigraphy.*[1]

The italics above are the writer's. Here again we run up against the stratigraphic misapprehension already alluded to. As to the dinosaurian evidence, as we shall presently see, its trend is the same as that afforded by the fishes. It is axiomatic that only the species common to any two or more formations are of any use in correlating them. *Lepidotus occidentalis* Leidy, described in 1856 from the Judith River beds, has been found by Williston[2] in the Lance formation of Converse County, Wyo., and by Barnum Brown in the Lance formation in the Hell Creek region. With this *Lepidotus* Williston found also another species, *Myledaphus bipartitus*, named by Cope from the Judith River beds. This seems to be a ray according to Hay,[3] who says: "The rays are almost wholly inhabitants of salt water; hence the persistence of this Judith River fresh-water form is somewhat remarkable." Another species of *Diphyodus*, a genus founded on a jaw fragment from a Canadian locality, is said by Hatcher to be common both in the Judith River beds of Montana and in the Laramie [Lance] deposits of Converse County, Wyo., and a species of the same genus was found by Barnum Brown in the Hell Creek beds. The tailed amphibians, which Hay says are at all times rare fossils, are all referable to the genus *Scapherpeton*, and five species were described by Cope from fragmentary material obtained in the Judith basin of Montana. Williston found one species in the Lance formation and Brown reported a species from the Hell Creek beds. Hatcher considers the batrachia of the Judith River beds of no special importance in determining the age of the deposits or in correlating them with other formations. Dr. Hay, however, referring to them says:[4]

While it is true that these fishes and amphibians are mostly represented by fragmentary remains, these remains are usually characteristic and capable of accurate comparison. That *Myledaphus* should reappear after an interval allowing the deposition of 1,000 feet of marine strata, and probably some hundreds of feet of fresh-water strata, is remarkable enough; but that it should reappear in company with its old companions, the rare *Diphyodus and Scapher-*

[1] *Bull. U.S. Geol. Surv., No. 257*, p. 67.

[2] *Bull. Amer. Mus. Nat. Hist.*, XXIII (1907), 842.

[3] Hay, *op. cit.*, p. 20.

[4] Hay, *op. cit.*, pp. 20, 21.

peton, not to mention the more highly developed fauna yet to be discussed, is very striking. Had there occurred at both levels only some pebbles of three peculiar forms or compositions, instead of the three genera, the conclusion would have been inevitable that there was some particular connection between the two formations.

When we realize that there is no interval between the Judith River beds and the Lance formation, allowing the deposition of thousands of feet of marine strata, we see that there is no remarkable reappearance of *Myledaphus* and its companions, but that they have simply coexisted in beds of the same age at different localities. As to *Champsosaurus* and the Crocodilia, it will serve our purpose here just to quote Dr. Hay, who says:

> Coming next to the reptiles, it may first be noted that species of *Champsosaurus* occur in the Judith River beds, in the Lance Creek beds, in those of the Hell Creek region, and in the Puerco. It is probable that the species vary from one formation to the other. The same statement can probably be made regarding the crocodiles. *These genera, common to all three of the formations under discussion, may be left out of consideration; although it must not be overlooked that, none the less, they aid in binding together the formations in which they are found.* As to the crocodiles, it may be mentioned that Williston recognized, in teeth and scutes found in the Lance Creek beds, Leidy's *Crocodylus humilis*, originally described from the Judith River region. From the Judith River beds of Alberta, Lambe described *Leidyosuchus canadensis*. Mr. C. W. Gilmore will soon describe a second species of the genus, collected last summer in the Lance Creek beds of Converse County, Wyo.

The sentence italicized by the writer in the above quotation is the one specially pertinent to the present discussion.

As regards the turtles which have been especially studied by Dr. Hay, he says:

> My study of the fossil turtles indicates that the species of these animals rarely pass from one epoch to another. If they have ever done so, they passed from the Judith River into the Lance Creek epoch. There are five or six species of Judith River turtles which are represented in the Lance Creek and Hell Creek beds by turtles of identical or very closely related species. Most of these are marked by such peculiar sculpture that they are easily recognized and some of them likewise are represented by excellent materials.

Dr. F. H. Knowlton has recently shown conclusively[1] that, of the sixteen species of turtles accredited by Hatcher to the Judith

[1] Knowlton, *Proc. Wash. Acad. Sci.*, XII (1911), 51–65.

River beds, only nine are actually found in the Judith basin of Montana. Four of these are types and of these, only two are confined to the Judith beds. The other seven are common to both the Judith and Lance formations which, in view of what Dr. Hay has written, is good proof of their identity in age.

The most abundant and conspicuous reptiles in both the Judith River and the Lance formations are the dinosaurs, and practically half of those listed by Hatcher are common to both formations. Writing of these dinosaurs Dr. Hay says:[1]

> Five families of these, belonging to four super-families and to two suborders, are represented in the Judith River epoch, and each of these families reappears in the Lance Creek epoch. Furthermore, many of the genera are common to the two formations and it is believed that the same is true of a considerable number of species.

Hatcher in his summary in the consideration of the dinosaurs[2] says that "they of all the vertebrates of these beds [Judith River] afford the best basis for a comparison of the fauna of these deposits with that of the Laramie [Lance] above (?) and the Jurassic below." He says the great group of Sauropoda which formed a conspicuous feature at the close of the Jurassic and the beginning of the Cretaceous is entirely wanting, and that the Stegosauria, which formed a striking feature among the Jurassic dinosaurs, have almost or quite disappeared, being entirely replaced by the quadrupedal Ceratopsidae and the bipedal Trachidontidae. "No unmistakable representative of the Stegosauria is certainly known from the Judith River beds. *Palaeoscincus*, referred to this suborder chiefly on the evidence of teeth alone, may or may not pertain to the Stegosauria, while *Stereocephalus* appears to have been founded on material belonging in part to the Crocodilia and in part to the Dinosauria." On the following page Hatcher states that these Dinosauria are not distinguishable from remains from the Laramie [Lance] at present referred to the Ceratopsia. Whether or not *Palaeoscincus costatus*, described from the Judith River badlands by Leidy in 1856, is represented in the Lance formation by numerous teeth[3] cannot be positively stated. The genus is represented

[1] *Op. cit.*, p. 23.

[2] *Bull. U.S. Geol. Surv., No. 257*, pp. 101–3.

[3] Hatcher, *op. cit.*, pp. 83, 88; Hay, *op. cit.*, p. 23.

in the Hell Creek region and in Converse County, Wyo. Hatcher[1] says:

> The Trachodontidae had already attained to considerable diversity in Judith River times. Indeed they appear to have been more abundant as regards both numbers of individuals and genera and species than they were in the Laramie [Lance]. Judging from the rather meager material at hand for comparison, they were, however, somewhat less specialized.

As to the Theropods, he says that so little is at present actually known from either the Laramie [Lance] or the Judith River beds "that it is quite impossible to make anything like an adequate comparison between them. The group, however, is represented in both formations by quite similar forms, though differing perhaps both generically and specifically." This statement appears to be little more than an assumption, inasmuch as about half the identified species are common to both formations. Although as Hay says,[2] much has yet to be learned of the Ceratopsia, especially of the Judith River forms, the knowledge of which is still somewhat vague, most of the remains from that region being of incomplete skulls. However, the interest in them has been so great that they have been studied with extraordinary care. This fact doubtless influenced Hatcher's statement: "It is in the Ceratopsidae more than in any other group that we are at present able to contrast the Judith River and Laramie [Lance] forms."[3] Hatcher's conclusion based on this comparison is as follows:

> The primitive nature of the Judith River Ceratopsidae as compared with the Laramie [Lance] is especially seen in the *smaller size of the individuals, the less perfectly developed armature of the skull, and the imperfectly developed parietal crest.*

The italics are Hatcher's.[4] This supposed contrast in the forms from the two formations is reiterated by Hatcher throughout his paper and in his monograph on the Ceratopsia edited by R. S. Lull and published by the Geological Survey.[5] Osborn, in making the same contrast, comparing especially the nasal and supraorbital horns mainly of the species of *Monoclonius* and *Ceratops* (found in

[1] Hatcher, *op. cit.*, p. 102.

[2] Hay, *op. cit.*, p. 24.

[3] Hatcher, *op. cit.*, p. 102.

[4] *Ibid.*, pp. 102, 103.

[5] *Monograph U.S. Geol. Surv.*, XLIX (1907).

the Judith River beds) which he says are very similar if not generically identical, says:[1]

> It will be observed that five of these species [of *Monoclonius* and *Ceratops*] are known to possess large nasal and small supraorbital horns. This stage of horn evolution *may* be contemporaneous and independent of that on the southern Laramie [Lance] dinosaurs in which the nasal horns are invariably smaller than the frontal horns, but coupled with the smaller size and open temporal *fossæ* it would appear to be more primitive.

The italics above are Osborn's and they seem to be justified by the fact that we do find species of Ceratops and of Triceratops coexisting in the same beds as in the Arapahoe formation of Colorado which, although of post-Laramie age, is probably older than the Lance formation. Dr. Hay's remarks[2] on the Ceratopsia are interesting in this connection. He says:

> Apparently nine species are known from the Judith River deposits of Montana and British America; and about fifteen species are credited to the Lance Creek beds of Wyoming, and to the Arapahoe and the Denver, of Colorado. Hatcher and Lull conclude that those of the Judith epoch are somewhat more primitive than those of the beds higher up, being somewhat smaller, with a less completely developed nuchal frill, with the nasal horn relatively larger and the supraorbital horns relatively smaller than in the younger forms. It is, however, to be noted that the nasal horn of Ceratops, of the Judith River epoch, is not yet certainly known. For the most part the genera are based on the characters mentioned above. They may have the importance assigned to them, but they do not indicate radical differences. Such differences might easily have arisen during an interval of moderate duration.

The supposed primitive nature of the Ceratopsidae of the Judith River basin of Montana as compared with those of the Lance formation of Wyoming and the supposed stratigraphic positions of the beds are apparently the main reliances of the advocates for the earlier age of the former and have led to considerable confusion in their consideration by different writers. Mr. R. S. Lull[3] has thus been led astray in his phylogeny of the Ceratopsia, which is based apparently more upon supposed geological position, than upon the phylogenetic characters. He is evidently misled because

[1] *Contributions to Canadian Paleontology*, III (1902), 20.

[2] Hay, *op. cit.*, p. 24.

[3] Advance print *Proc. 7th I.Z.C.*, Boston, 1902, Cambridge, 1910, p. 2.

of his belief that two thousand feet of marine shales and sandstone of Bearpaw and Fox Hills age intervene between the Judith River beds and the Laramie [Lance] formation. These deposits, in his opinion, represent a period of subsidence during which the advancing sea drove the land animals to the west and north. He says:[1]

Of these creatures which link the Judith River and Laramie [Lance] faunas, no remains have thus far been found so that we have no record of the evolution which must have occurred during the period of subsidence. At the close of the Fox Hills epoch, conditions much like those of the Judith River times again prevailed, and the horned dinosaurs, among other forms, sought their ancestral haunts. Four genera of Laramie [Lance] Ceratopsia are known, ranging themselves into two races or phyla which underwent a parallel evolution.

In this connection my friend Mr. J. W. Gidley of the U.S. National Museum has kindly prepared for me the following statement:

Regarding the validity of the Ceratopsia phyla as worked out by R. S. Lull, it seems to me to be highly conjectural and not founded on a basis of valid reasoning. While it may be conceded that Ceratops is in general more primitive genus than Triceratops, it is highly improbable that, having already developed a far greater nasal horn than in any species of the latter genus, this horn should have become atrophied while the brow horns were being developed to become the principal ones. Only that Ceratops is supposed to have come from much older beds, it would be just as reasonable to suppose that the reverse might have been the case, and so far as the horns alone are concerned Ceratops might just as well have been the descendant of a Triceratops form. It seems far more reasonable to suppose that, whether contemporaneous or separated by a long time interval, Ceratops and Triceratops represent two quite distinct phyla, developing horns along different lines.

As already intimated, the principal cause of confusion is to be found in erroneous ideas as to the stratigraphic position of the beds from which the collections were made. As a matter of fact, however, the time has not yet arrived when the phyla can be correctly constructed. Not only is the material already in hand too fragmentary, but it is too meager in the number of forms supposedly identified, nor are there sufficient specimens of each species to determine the distinctions due to individual variation or to differences in sex or age. When we find that Ceratops and Triceratops (one of which is supposed to be ancestral to the other) were con-

[1] *Ibid.*, p. 4.

temporaneous in Arapahoe time, and it is stated that the affinities of *Monoclonius* are with *Triceratops* and that *Ceratops montanus* is the ancestor of *Torosaurus*, while there is a possibility that *Monoclonius* may yet be identified with *Ceratops*, the present unavoidable confusion becomes noticeably evident.

Rearranging Lull's table of the "Geological Sequence of the Ceratopsia"[1] to accord with the views set forth in this paper, we have the following:

Formations	Localities	Species
Lance	Hell Creek, Mont.	Triceratops sp. Triceratops brevicornus Triceratops serratus
Lance	Converse Co., Wyo.	Trosaurus latus Trosaurus gladius Diceratops hatcheri Triceratops brevicornus Triceratops flabellatus Triceratops calicornis Triceratops sulcatus Triceratops prorsus Triceratops horridus Triceratops elatus Triceratops obtusus
Lance	Near Judith, Mont.	Ceratops montanus Ceratops paucidens Ceratops recurvicornis Monoclonius sphenocerus Monoclonius crassus
Denver	Denver, Colo.	Triceratops alticornis Triceratops horridus
Arapahoe	Near Denver, Colo.	Triceratops alticornis Triceratops galeus Ceratops montanus*
Post-Laramie	Black Buttes, Wyo.	Agathaumus sylvestris
Laramie	Black Buttes, Wyo.	No Ceratopsia
Fox Hills	Black Buttes, Wyo.	No Ceratopsia
Pierre	Black Buttes, Wyo.	No Ceratopsia

* The type specimen of *Ceratops montanus* is in the collection of the U.S. National Museum. As to the specimen from Colorado, Professor Lull thinks "it must be a case of mistaken identity." This, in the writer's opinion, is due to the fact that the Judith River beds and those of the Lance formation are mistakenly supposed to be separated by thousands of feet of beds.

The principal differences between this table and Lull's is the taking-away of the Lance formation from the Laramie; the inter-

[1] Lull, *op. cit.*, p. 184.

polation of the true Laramie between the Fox Hills and the Black Buttes beds, which are referred by us to the post-Laramie; and the placing of the Arapahoe and Denver below the Lance, reversing the position given them by Lull and the reference also of the Judith River beds to the Lance. This arrangement appears to me not only the true one but far better, as it ties the species together in a more logical manner. It will not be necessary to conclude as Lull has that the "identification of *Ceratops montanus* seems hardly possible, as *Ceratops montanus* is a Judith River type and is vastly older than the Arapahoe." Although the Arapahoe and Denver lie at the bottom of the series and the Hell Creek beds nearer the middle or at the top of the Lance formation, we do not yet know their exact equivalency, but that they are not separated by thousands of feet of beds can confidently be stated. Mr. Cross, long ago, pointed out "the fact that the Judith River strata may perhaps represent the Arapahoe or some other post-Laramie formation."[1]

Eliminating from Hatcher's list of Judith River vertebrates (which includes no mammals in the type region) all the species which are duplicated under other names and all which come from beds not of Judith age or that occur outside the typical area (the Judith basin of Montana), his list is reduced to 33. Of these we find that 22 occur also in strata referrred to the Lance formation. These species are tabulated below. Besides the Converse County, Wyo., and Hell Creek, Mont., lists, others might be given showing that Judith River species occur in other parts of Montana as well as in northeastern Colorado, but the lists given here are deemed sufficient to prove the identity of the beds.

Writing in 1902 (and the list was not so great then as now) on the identity of genera and species not only between these beds but including also the Belly River of Canada, Williston says:[2]

It would seem almost incredible that so many of these should have persisted unchanged through the long interval represented by so many thousand feet of Fox Hills deposits, to say nothing of those of the Fort Pierre. I doubt if a parallel can be found elsewhere in vertebrate paleontology. It is true that many of these forms from both the Judith River and the Laramie [Lance]

[1] *Monograph U.S. Geol. Surv.*, XXVII (1896), 239.

[2] *Science*, N.S., XVI (December 12, 1902), 953.

are known only from fragmentary remains and that future researches may show specific differences in some of them, but the resemblance in any event is marvelous.

This resemblance is no longer marvelous, when we know that in both cases we are talking of beds of the same age.

Judith River Formation		Lance Formation
Judith River Basin, Montana	Converse County, Wyoming	Hell Creek, Montana
Lepidotus occidentalis	Lepidotus occidentalis	Lepidotus occidentalis
Myledaphus bipartitus	Myledaphus bipartitus	
Accipenser albertensis	Accipenser albertensis	
Diphyodus longirostris	Diphyodus longirostris	Diphyodus sp.?
Scapherpeton tectum	Scapherpeton tectum	Scapherpeton tectum
Ischyrotherium, cf. antiquum	Ischyrotherium, cf. antiquum	
Trionyx foveatus	Trionyx foveatus	Trionyx foveatus
Adocus lineolatus	Adocus lineolatus	Adocus lineolatus
Compsemys obscurus	Compsemys obscurus	Compsemys obscurus
Compsemys victus	Compsemys victus	Compsemys victus
Champsosaurus	Champsosaurus humilis	Champsemys
Crocodilus humilis	Crocodilus humilis	Crocodilus sp.
Troodon formosus	Troodon formosus	
Deinodon horridus	Deinodon horridus	
Aublysodon mirandus	Aublysodon mirandus	
Paronychodon lacustris	Paronychodon lacustris	
Zaphalis abradus	Zaphalis abradus	
Deinodon explanatus	Deinodon explanatus	
Deinodon cristatus	Deinodon cristatus	
Deinodon hazenianus	Deinodon hazenianus	
Ornithomimus altus		Ornithomimus altus
Palaeoscincus costatus	Palaeoscincus costatus	Palaeoscincus sp.
Trachodon mirabilis	Trachodon mirabilis*	Trachodon sp.

* Hatcher, *Annals of the Carnegie Museum*, I, No. 3, p. 382.

In what has been written above the endeavor has been to prove from the words of the vertebrate paleontologists themselves the identity of the Judith River and Lance formations. Knocking from beneath the structure so elaborately reared the weak and ineffective stratigraphic props, the entire edifice must fall. Either the beds are identical in age, or vertebrate paleontology has no place in stratigraphic geology, and *non geologia sine paleontologia* becomes *non paleontologia sine geologia*. That they are, however, of the same age is the irresistible conclusion to which we come. Whether they are of Cretaceous or Tertiary age is beside the question at this place, although the views and opinions of the writer as to their early Eocene Tertiary age have been expressed in another part of this paper.

SUMMARY AND CONCLUSIONS

The Judith River formation was named and considered by Dr. F. V. Hayden to be of Tertiary age and, from that time (1855) to 1903, every geologist who studied the beds coincided in the main with his views. A list of these geologists who studied the beds in the field is as follows: F. B. Meek, E. D. Cope, C. A. White, Walter H. Weed, L. F. Ward, George M. Dawson, G. B. Grinnell, Ed. S. Dana, and T. W. Stanton. Not until 1903 was there any question as to their position nor much discussion as to their age, except by the vertebrate paleontologists. In this year after a study in the folded and faulted region surrounding the Bearpaw Mountains in Montana, Stanton and Hatcher traced the outcrops noted near Havre on the northeast side of the mountains up Milk River, across the international boundary to Pakowki Coulee and correctly correlated the beds exposed at Havre with the Belly River beds already identified on Milk River by the Canadian geologists, but they incorrectly correlated these beds with the Judith River formation exposed mainly between the Bearpaw Mountains and the Missouri River, confusing the two formations as the Canadian geologist had previously done. These formations were the Judith River beds overlying the Pierre and the Belly River series lying below the Pierre shales. This confusion as to position, as noted, had occurred also in the Canadian outcrops and was straightened out by McConnell and Tyrrell. Stanton and Hatcher were led into the same error also on Fish Creek south of the Musselshell River and on Willow Creek north of the same river in Montana, as was very evident to us when we revisited this area in 1911. Our first conclusion, therefore, is that the Judith River beds and the Belly River series, although both of fresh-water origin and lithologically very similar, are entirely distinct from each other, occupying stratigraphical positions separated by 1,000 feet or more of marine sandstones and shales.

The sandstones and sandy shales immediately underlying the typical Judith River beds are of marine origin and contain a fauna which Dr. Stanton says has long been considered a "typical Fox Hills" fauna. In addition to this fauna we found *Halymenites major*, a characteristic plant of the Fox Hills formation, throughout

the Rocky Mountain region. Further, a comparison of the Fox Hills fauna from the Judith River Basin with those of other sections in the Rocky Mountains, particularly with those from Colorado where the most complete Fox Hills sections is found, shows that only 4 of the 18 species occurring in the Judith River section are not found elsewhere. These Fox Hills beds in the Judith River basin were named Claggett by Dr. Stanton, but apparently this is only another name for the Fox Hills formation as developed in the disturbed portions of the Judith basin. Our second conclusion, therefore, is that the Fox Hills formation, with its characteristic fauna and flora, immediately and unconformably underlies the Judith River beds and that it rests conformably upon exposures of characteristic Pierre shales throughout the Judith basin.

It has further been shown that the Judith River beds occupy the identical stratigraphical position of the Lance formation. Both rest unconformably upon Fox Hills sandstones. Possibly we have in the Judith River beds the equivalent of only the lowest portions of the Lance formation. It has also been shown that out of 33 species of vertebrates occurring in the Judith River beds, 23 are common to both the Judith River and the Lance formations. The invertebrates of both are mainly fresh-water forms which closely resemble each other in the two formations, and the plants of both, so far as they are known, suggest a Lance or Fort Union rather than the Belly River age. Undoubtedly there are areas on all sides of the Bearpaw Mountains in which, when we get beyond the area of disturbance due to the uplift, continuous sections will show below the Pierre shales, the Belly River series with characteristic floras, and above, the Judith River beds with floras referable to the Lance and Fort Union formations. There are indications that the conditions are like those found on the Canadian side of the international boundary. We have no hesitation in stating the third conclusion, viz., that the Judith River formation is the representative if not the exact equivalent of the whole or of some, perhaps lower, portion of the Lance formation and that the latter name should be replaced on the ground of priority of use by the name Judith River formation.

We have also seen that the Belly River series is always overlain by the Pierre shales not only in the Canadian sections but also

south of the international boundary, especially in Fish Creek south of the Musselshell River, and at Willow Creek 12 miles north of Musselshell. By no stretch of the imagination, can the beds below the Belly River series be taken to represent the Pierre shales, either lithologically or paleobotanically. In both the United States and Canada, the affinities of the flora are with the Dakota and not with the Montana. The faunas, in Canada especially, show a mingling of Niobrara and Pierre forms, and although there is a bare possibility that the upper part of the Belly River series may be of basal Montana age, it is more than likely that there is here simply a mingling of forms as at the base of the Fox Hills formation, where there is a mingling of Pierre forms in the transition from one formation to the other. We are therefore fully warranted in concluding, as pointed out by Dawson long ago, that the Belly River series is of Niobrara age. The Eagle formation as named by Walter H. Weed includes about 200 feet of fresh-water sandstones overlying the leaden grey marine shales of the Colorado formation. In the sandstones plants occur that are similar to those found in the Canadian Belly River, which Dr. Knowlton afterward correlated with the Dunvegan group of Dr. Dawson as found in Canada. Dr. Stanton afterward added to the formation about a hundred feet of sandstones, shales, and lignitiferous beds from the upper part of which he says he collected marine invertebrates that showed a closer relation to the Montana than to the Colorado group. There is a possibility that some of the beds may have been wrongly identified; as Dr. Stanton says, "the formation has often been confused with several other horizons." However, the Eagle as originally defined, together with some of the immediately underlying calcareous and gypsiferous shales, marks the base of the Niobrara formation as indicated by the flora of the sandstones.

Apparently the entire series from the base of the Eagle sandstone to the base of the Pierre shales is a unit representing the Canadian Belly River formation, but it may be advisable to restrict the name Belly River to the soft badland shales at the summit and retain the name Eagle for the basal sandstones and their overlying shaly beds and possibly apply some other name (not Claggett) to the intervening beds.

USE OF SYMBOLS IN EXPRESSING THE QUANTITATIVE CLASSIFICATION OF IGNEOUS ROCKS

WHITMAN CROSS

In a recent publication F. W. Clarke[1] has given, among various geochemical data, a new average for the existing chemical analyses of igneous rocks of the world, together with other averages for continents, countries, or districts. Clarke also gives a table, prepared by Iddings, showing by names and symbols the quantitative classification of magmas corresponding in composition to those averages. Speaking of these averages as representing magmas or rocks, it is a fact, of no special significance in itself, that many of them chance to fall very near boundary lines of several divisions of the quantitative system. Consequently the simple names and symbols of Clarke's table fail to show satisfactorily the true systematic relations of such rocks. These relations may, however, be very clearly expressed by means of the elaborated symbols, proposed since the publication of Clarke's paper, by the authors of the quantitative system.[2] The efficacy of these symbols in expressing certain relations may be illustrated by showing their application to the averages of Clarke.

As the basis for the calculations to follow and to further disseminate the interesting averages made by Clarke, they are repeated in the accompanying table. Water and several rare or unimportant constituents have been omitted by Clarke and the remainders calculated to 100 per cent. The capital letters by which Clarke designates individual averages in his tables have been retained.

The normative ratios of the table on p. 760 give the data by which rocks of these average compositions may be accurately classified in the quantitative system. From these ratios the elabo-

[1] "Some Geochemical Statistics," *Proc. Am. Phil. Soc.*, XLI (1912), 214–34.

[2] W. Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, "Modifications of the Quantitative System of Classification of Igneous Rocks," *Jour. Geol.*, XX (1912), 550–61.

AVERAGES OF CHEMICAL ANALYSES OF ROCKS, CLARKE

	A	B	C	E	F	G	H	I	J	L	M	N	O	P	Q
SiO_2	61.13	60.49	58.83	61.68	59.16	61.22	62.87	62.20	61.47	60.84	58.83	60.18	59.89	61.13	60.76
Al_2O_3	15.03	15.81	15.97	15.41	15.17	16.35	16.66	15.87	15.63	16.70	15.76	15.88	16.07	16.29	15.87
Fe_2O_3	3.50	4.90	3.36	2.67	2.16	3.30	2.67	2.12	2.67	3.75	3.96	3.90	4.18	3.76	3.40
FeO	4.38	2.77	3.91	3.55	5.36	2.58	2.40	3.46	3.22	2.68	3.75	3.44	3.18	2.93	3.19
MgO	2.86	3.81	3.88	3.97	4.92	3.47	2.06	3.93	4.02	2.10	4.09	2.82	3.59	3.18	3.78
CaO	4.81	4.95	5.27	5.02	5.69	4.95	4.01	6.06	5.12	4.39	5.73	5.83	5.30	5.54	5.23
Na_2O	3.75	3.26	3.95	3.49	3.46	3.83	4.11	3.49	3.62	4.98	3.74	3.36	3.70	4.01	3.67
K_2O	3.32	2.84	3.19	3.07	2.76	3.22	4.10	1.92	3.06	3.68	3.18	4.17	3.25	2.16	3.08
TiO_2	0.78	0.53	1.05	0.77	0.98	0.69	0.74	0.58	0.81	0.63	0.67	0.10	0.51	0.66	0.67
P_2O_5	0.25	0.22	0.37	0.27	0.23	0.31	0.27	0.27	0.27	0.14	0.22	0.21	0.20	0.14	0.23
MnO	0.19	0.42	0.22	0.10	0.11	0.08	0.11	0.10	0.11	0.11	0.07	0.11	0.13	0.20	0.12
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

NORMS OF AVERAGE ANALYSES

	A	B	C	E	F	G	H	I	J	L	M	N	O	P	Q
Q	12.60	15.06	7.74	13.50	8.16	12.24	12.60	16.26	12.60	7.20	7.80	9.48	10.38	13.98	11.94
or	19.46	16.68	18.90	18.35	16.68	18.90	24.46	11.12	18.35	21.68	18.90	25.02	19.46	12.79	18.35
ab	31.96	27.77	33.54	29.34	29.34	32.49	34.58	29.34	30.39	41.92	31.96	28.30	31.44	34.06	30.92
an	14.18	20.02	16.40	17.24	17.51	17.79	15.01	22.24	17.24	12.51	16.68	15.85	17.51	20.02	17.79
di	6.55	2.62	5.78	4.67	7.60	3.95	2.44	4.91	5.96	6.83	8.40	9.64	5.94	5.28	5.30
hy	8.00	9.32	9.84	10.97	15.38	7.76	4.99	11.27	9.55	2.90	8.85	5.52	7.77	6.86	8.91
mt	5.10	7.19	4.87	3.71	3.02	4.87	3.71	3.02	3.71	5.34	5.57	5.57	6.26	5.34	4.87
il	1.52	0.91	2.13	1.52	1.82	1.44	1.52	1.06	1.52	1.22	1.37	0.15	0.91	1.37	1.37
ap	0.57	0.50	0.91	0.67	0.54	0.70	0.67	0.67	0.67	0.34	0.50	0.50	0.50	0.34	0.54
	99.94	100.07	100.11	99.97	100.05	100.14	99.98	99.89	99.99	99.94	100.03	100.03	100.17	100.04	99.99

A. Average of 248 "superior" analyses of igneous rocks selected by Washington from Roth's tables. See *U.S. Geol. Survey, Prof. Paper No. 28.* Computed by Clarke.

B. Average of 536 British rocks, computed by Harker. "Tertiary Igneous Rocks of the Isle of Skye," *Mem. Geol. Survey, United Kingdom,* 1904, p. 416.

C. Washington's average of 1,811 rocks from all parts of the world. *U.S. Geol. Survey., Prof. Paper No. 14,* p. 106.

E. Average of all data relating to the composition of igneous rocks contained in the laboratory records of the U.S. Geol. Survey (Clarke).

F. Average of 250 analyses of rocks from the Atlantic slope, Maine to Georgia.

G. Average of 113 analyses of rocks from Yellowstone Park.

H. Average of 137 analyses of rocks from Colorado.

I. Average of 195 analyses of rocks from California.

J. Average for all North America. E combined with 398 analyses from Washington's tables.

L. Average of 231 analyses of rocks from Norway, Sweden, and Finland.

M. Average of 420 analyses of rocks from Germany and Austro-Hungary.

N. Average of 250 analyses of Italian rocks.

O. Mean of 1,437 analyses included in B, L, M, and N, plus 122 other analyses of European rocks.

P. Average of 82 analyses of rocks from South America.

Q. General mean of all analyses considered by Clarke.

rated symbols may also be readily determined. Referring to the original paper, already cited, for details of the new proposition, it may be briefly explained in this place.

It is recognized that it is desirable to express in the quantitative system two frequently observed relations of rocks which cannot be shown by the simple magmatic name or the symbol hitherto used. Two rocks often fall in opposite extreme portions of a division, while two others may be found occurring in two adjacent divisions but very near the boundary line. It has been proposed to establish *intermediate* and *transition* zones, the former extending

TABLE OF NORMATIVE RATIOS

	Class $\frac{\text{Sal}}{\text{Fem}}$	Order $\frac{\text{Q}}{\text{F}}$	Rang $\frac{K_2O'+Na_2O'}{CaO'}$	Subrang $\frac{K_2O'}{Na_2O'}$
A	3.59	0.19	1.88	0.57
B	3.87	0.23+	1.15	0.57
C	3.25	0.11	1.661	0.53
E	3.64	0.21	1.43	0.59
F	2.53	0.13	1.36	0.54
G	4.36	0.176	1.50	0.55
H	6.50	0.17	2.04	0.67
I	3.77	0.26	0.95	0.36
J	3.67	0.19	1.47	0.57
L	5.01	0.09	2.64	0.49
M	3.06	0.11	1.58	0.56
N	3.67	0.137	1.74	0.83
O	3.68	0.15	1.51	0.58
P	4.21	0.21	1.22	0.35
Q	3.76	0.178	1.44	0.56

on each side of a given division line one-half the distance to the center points of adjacent divisions and the latter one-fourth of this distance. The boundaries of both intermediate and transition zones are determined accurately by the ratios of the two quantities concerned in the formation of classes, orders, etc. These determining ratios are given in the cited publication.

The transitional position of a rock may be expressed by a compound name, but where it is transitional in more than one respect, as frequently happens, it is desirable to use only the two subrang names expressing the lowest systematic stage in which such transitional relation exists. This usage is illustrated in the following table. In the symbols the transitional relation is indicated by giving in parentheses, beside the number of the division in which

a given rock falls, also the number of the division toward which it is transitional.

The intermediate position of a rock is expressed by prime marks placed either before or after the number of a division according to the direction in which the rock is intermediate.

The result of applying these devices to the quantitative classification of Clarke's average rocks is shown in the accompanying table. It appears at once from the symbols of this table that all but three of the average rocks fall in the central half of Class II; that the three exceptions are intermediate to Class I, and that one is within the transitional bounds. The ratios show that not one of these rocks is half-way from the center point of Class II toward Class III.

QUANTITATIVE CLASSIFICATION OF AVERAGE ROCKS

	Average of Analyses	Name	Class $\frac{Sal}{Fem}$	Order $\frac{Q}{F}$	Rang $\frac{Alkalies}{CaO'}$	Subrang $\frac{K_2O'}{Na_2O'}$
H	137 rocks of Colorado....	Dacose-adamellose	(I) II	4(5)	2′	3(4)
A	248 analyses, Roth's tables	Adamellose-dacose	II	4′	2(3)	(3)4
G	113 rocks of Yellowstone Park..........	Harzose-tonalose	′II	4(5)	(2)3	(3)4
J	North America.........	Harzose-tonalose	II	4′	(2)3	(3)4
E	U.S.G.S. analyses.......	Harzose-tonalose	II	4′	′3	(3)4
B	536 British rocks, Harker	Harzose-tonalose	II	4	3	(3)4
O	1659 rocks, Europe......	Harzose-tonalose	II	4(5)	(2)3	(3)4
Q	World's average, Clarke..	Harzose-tonalose	II	4(5)	′3	(3)4
I	195 rocks of California...	Tonalose	II	4	3	4
P	82 rocks of South America	Tonalose	II	4′	3	4
N	250 rocks of Italy.......	Shoshonose-monzonose	II	(4)5	2(3)	3
M	420 rocks of Germany and Austria..............	Shoshonose-andose	II	(4)5	(2)3	(3)4
F	250 rocks of Atlantic Coast, U.S............	Shoshonose-andose	II	(4)5	′3	(3)4
C	World's average, Washington...............	Monzonose-akerose	II	(4)5	2(3)	(3)4
L	231 rocks of northern Europe..............	Akerose	′II	′5	2	′4

With regard to the relation of normative quartz and feldspar, determining the order, it is seen that eight rocks fall within the narrow transitional limits between Orders 4 and 5, half of them on one side and half on the other. Of the remainder all but two are intermediate toward the same boundary line. Of the two rocks coming within the central half of Order 4, B and I, the former is

almost on the intermediate line. The extreme range from I to L is less than one-half that of Order 4.

In regard to rang, expressing the quantitative relation of alkalic to calcic feldspars, the new symbols further emphasize the relationship of most of these averages. The range from the most alkalic rock, L, to the most calcic, I, is somewhat less than that of a full rang.

In the relation of potassic to sodic feldspars, a large majority are found to be transitional between dosodic and sodipotassic subrangs, although but two are of the latter. The average of Italian analyses would represent a sodipotassic magma, but even in this case falling on the sodic side of the centerpoint of Subrang 3. The next most richly potassic average is that of Colorado analyses, but it is to be noted with regard to this average that a large number of analyses of phonolite and other sodic rocks from the small Cripple Creek center somewhat obscure the characteristic relative abundance of potash which the writer has long recognized in Colorado rocks.

The use of these new symbols by the writer has convinced him that they afford a good means of expressing in a concise way close relationships or marked differences which it is otherwise necessary to explain in many words. It is to be hoped that petrographers using the quantitative system may become impressed by the status of the transitional rock. It is just as important as any other type, but unless the transitional character is expressed by name or symbol, erroneous impressions may be given. A rock specimen shown by analysis to occupy a transitional position may have come from a mass which as a whole belongs on the opposite side of the division line. It is evident that special care is desirable in the calculation of the norm and the ratios of transitional rocks.

In closing, it seems well to point out to petrographers that it is bad practice to name any division of the quantitative system after the occurrence of a type which is transitional in any respect. The authors of that system have themselves erred in a few cases, but some subrang names recently proposed by other petrographers are particularly unfortunate. It would be well in future, in the writer's opinion, to base a name only on a type falling within the central half of each division of the system.

THE PHYSICAL SETTING OF THE CHILEAN BORATE DEPOSITS

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North of the Tropic of Capricorn, the Andes of Chile and Bolivia stand forth as two massive chains with a lofty plateau between. The two great ranges of Andes are known as the Cordillera Occidental and the Cordillera Oriental, or Cordillera Real. The lofty tableland between passes under the name of Altaplanicie, or Great Central Plateau of Bolivia. It is in some respects one of the most remarkable topographic features of South America. Throughout nearly ten degrees of latitude its surface maintains an elevation of approximately 12,000–13,000 feet above sea-level. But apart from its greater elevation this broad inter-Andine tableland shows a resemblance to portions of the great basin region in the western United States.

This plateau is boxed in on the east by the great wall-like ridge of the Eastern Cordillera which culminates in the giant peaks of Illimani (21,200 feet) and Illampu (21,490 feet). On the west the plateau is bounded by a remarkable string of volcanoes which constitute the Western Cordillera. The two systems of mountains are totally unlike. While the eastern range, or Cordillera Real, is composed of folded Paleozoics, with the still older granites and gneisses exposed in the axis of the range, the Western Cordillera is conspicuous chiefly as a chain of volcanic cones perched upon the western edge of the great plateau. These volcanic cones rest upon folded Mesozoic strata, chiefly of Jurassic and Cretaceous age. The body of the plateau itself is composed principally of beds ranging in age from the Devonian to the Cretaceous.

Throughout the extent of the plateau, in Chile, Bolivia, and Peru, are numerous lakes, saline marshes, and beds of former lakes, most of which possess no outward drainage. The large bodies of water which still persist, like Lake Titicacā and Lake

Pampa Aullagas, are well enough known, but in addition there are many minor lake flats, dry or nearly so, which escape notice. It is on some of these old lake bottoms that the great borate deposits of South America occur. But here the geographic distribution of the lakes which contain borax is of significance, as it is found that the deposits of borax are largely confined to those lakes which lie close to the volcanoes of the Western Cordillera. Away from the volcanoes, whether eastward over the central plateau, or westward down the long desert slopes leading toward the coast where the nitrate beds abound, the borates rapidly disappear. The borates thus seem to be related to the volcanoes. The nitrates occur on open salinas at moderate elevations, 3,000–5,000 feet, and not far back from the coast. The borax fields, on the other hand, are located high up on the edge of the tableland close to the base of the big volcanoes. Both nitrates and borates are dependent for their accumulation and preservation upon the extreme aridity of the region, but the sources of the nitrogen and the boron are quite different.

The Salinas of Ascotan may be taken as a typical case to show the probable source of the borates. The railroad from Antofagasta to Bolivia creeps steadily upward from the coast and reaches its highest point in crossing the Western Cordillera at the station of Ascotan, which is about 13,000 feet above the sea. The Western Cordillera here consists of volcanoes most of which have only recently become extinct, while, from a few, smoke is still escaping. In the neighborhood of Ascotan the cones rise to heights of 17,000–19,500 feet. But in spite of the great altitude only an occasional patch of snow is seen on these lofty peaks owing to the extremely scanty precipitation, for this region lies at the northern end of the desert of Atacama.

After climbing up to Ascotan the railway runs parallel to the line of volcanoes and the great borax lake of Ascotan comes into view. This lake is perhaps 10 miles long and 3 miles wide, extending northward parallel to the range to a point beyond Cellobar. It fringes the base of a line of volcanoes which begin at the south in the cone of San Pedro y Pablo (19,400 feet) and end north of the lake in the smoking volcano of Ollagüe (19,200 feet). The

slopes of the volcanic cones rise directly from the shores of the borate lake. In the so-called lake very little water is seen; most of its surface is a white field of borate which rests upon the watery mass below like ice upon a partially frozen pond. It is really a borate incrusted lake bed.

The craters of the adjoining volcanoes are all quite recent, and some of them are probably dormant rather than extinct. Ollagüe at least still emits a thin thread of smoke from an orifice in its upper slopes. Drainage lines are not yet well established,

FIG. 1.—Volcano on border of Ascotan Borax Lake. The drainage from the crater passes directly into the lake.

but whatever drainage and seepage there may be from these cinder cones would necessarily pass, in large part, directly into this lake basin. Underground drainage from several large volcanoes would find its way into the borax lake. One of the craters was seen to have its wall broken down on the side toward the lake so that much of the surface runoff from the crater walls as well as the underground seepage through the cinder cone would go directly to the lake (Fig. 1).

The lake has no apparent outlet so that the small amount of water on the lake bed represents a state of balance between the

scanty precipitation which falls upon the basin and its volcanic borders, and the loss by evaporation. Necessarily there is a concentration of salts as evaporation goes on. All salts dissolved by waters which trickled through the volcanic cones and reached the lake flat would gradually become concentrated there as the water evaporated and would finally be deposited as a solid incrustation.

The water entering the lake, whether directly or by the underground route, can have come in contact with little besides volcanic material, since all the higher land around the lake is made up of volcanic rocks. Therefore the source of the boron is to be sought in the volcanoes. Unfortunately lack of time did not permit an examination of the craters themselves. But it is known that borates and free boric acid in the form of sublimates from hot vapors are often conspicuous deposits around fumaroles and active volcanic craters in various other parts of the world. Judd states that in the solfataras of Tuscany, boracic acid is, next to the true gases, the most noteworthy compound emitted from the vents.[1] Vulcano, in the Lipari Islands, emits boracic acid which, attacking the materials of the surrounding rocks, has formed borates of the alkalies and alkaline earths.[2] These new chemical compounds are continually accumulating on the sides and lips of fissures from which the acid gases and vapors are issuing. The mineral sassolite ($B_2O_3 . 3H_2O$) is common at Vesuvius.[3] Compounds of boron are therefore to be expected in these Chilean volcanoes and it may be supposed that rain-water falling upon these craters and percolating through the cinder cones would dissolve the soluble boron salts and later deposit them on the lake bed where the water finally evaporated.

But in addition to borates, other salts soluble in water, such as chlorides, sulphates, etc., are also present in volcanic craters. These should also be dissolved by rain-water and carried down onto the evaporating flat as well as the borates. This has evidently happened in the Ascotan field, for the percentage of borate varies

[1] J. W. Judd, *Volcanoes*, p. 216.

[2] *Ibid.*, pp. 42–44.

[3] J. L. Lobley, *Mount Vesuvius*, p. 321.

considerably in different parts of the area. The boron, however, occurs almost entirely as a single compound, the mineral ulexite, or boronatrocalcite ($NaCaB_5O_9.8H_2O$). But there would seem to be in operation some process by which the various salts derived from the volcanoes are separated before being deposited on the lake flats, for in some parts of the field the boronatrocalcite occurs remarkably pure. It is in such places that it is now being worked for borax. The material is so free from other salts that it is only

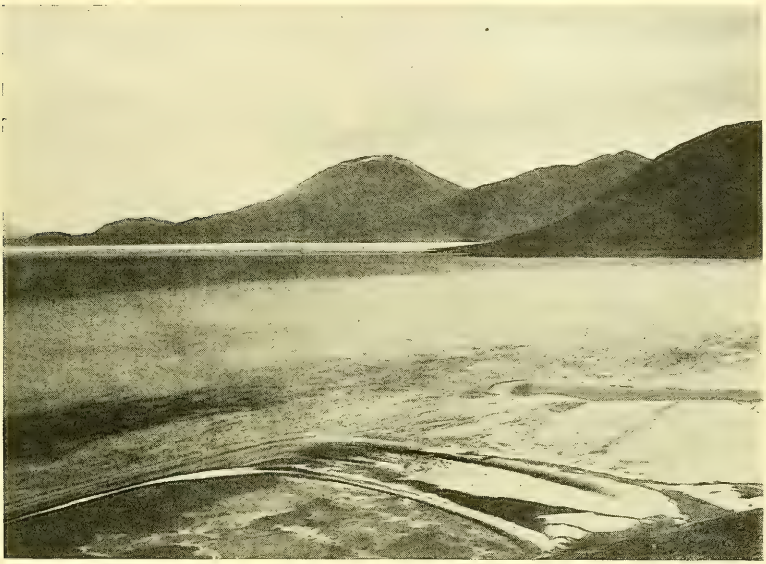

FIG. 2.—Borax incrusted lake flat with the volcano Ollagüe in the distance. Other volcanic peaks to the right.

necessary to dry it before shipping it to Europe, where it is later refined. But in other parts of the region the borate occurs in beds alternating with layers of salt and salty earth with some glauberite and gypsum associated.

Some distance beyond Cellobar is another dazzling white bed of borax whose flatness the railroad to Bolivia utilizes by running straight across it. Close by is the big volcano Ollagüe which is still smoking (Fig. 2). On other sides the borax flat is hemmed

in by several scarcely less massive cones which would seem to provide ample sources for the borate in the basin.

Beyond the station of Ollagüe the train, turning more to the east, leaves the volcanic Cordillera and makes its way over the Great Central Plateau to Uyuni and Oruro. This region is a great detritus-strewn plain with low ridges and ranges trending generally north and south. Salt marshes and old lake beds continue, but as the volcanoes are left behind, the deposits of borax rapidly disappear. There are no known borate deposits associated with the non-volcanic Eastern Cordillera.

WATER-WORN COAL PEBBLES IN CARBONIFEROUS SANDSTONE

WILLIAM F. PROUTY
Geological Survey of Alabama

The accompanying photograph illustrates rounded pebbles of bituminous coal, one of which is shown imbedded in a coarse-grained sandstone. These pebbles are exposed in large numbers in a stone quarry which is located[1] on the banks of the Warrior River just above Lock No. 12, Tuscaloosa, Ala., and but a short distance from the State University. The sandstone is in some places very coarse and conglomeratic. In many cases the coarse fragments making the conglomerate are angular, having received but little wear. At the locality where the coal pebbles occur most numerously there is much cross-bedding of the sandstone and a marked difference in the coarseness and fineness of the sediment together with considerable contemporaneous erosion, thus giving evidence of a delta deposit. In the sandstone which carries the coal pebbles are found many fragments of carboniferous trees. The geological position of this sandstone is near the top of the coal measures of the Warrior Coal Field, being about 60 feet above the Duree coal seam and about 30 feet below the Brookwood coal seam of the Brookwood group (the highest known group of coals in the Warrior field). The size of the pebbles varies from ½-inch to 15 inches or more in diameter. One pebble observed had the shape of a prolate spheroid about 18 inches long and nearly 12 inches thick. This was imbedded in a coarse-grained sandstone.

An analysis of the coal, from the pebble shown in the photograph imbedded in the rock, is as follows:

Moisture	2.42
Volatile matter	38.73
Fixed carbon	56.06
Ash	2.79
	100.00

[1] The occurrence of coal pebbles at this locality was first called to my attention by Dr. E. A. Smith of the University of Alabama.

The above analysis shows the specimen to be a high-grade bituminous coal. Its composition is almost identical with that of the seam which lies some 60 feet below it, the Duree seam of coal which gives the following analysis:

Moisture	2.30
Volatile matter	38.58
Fixed carbon	54.11
Ash	5.01
	100.00

The origin of the pebbles is not perfectly clear. That the material forming the pebbles was water-worn before being imbedded in

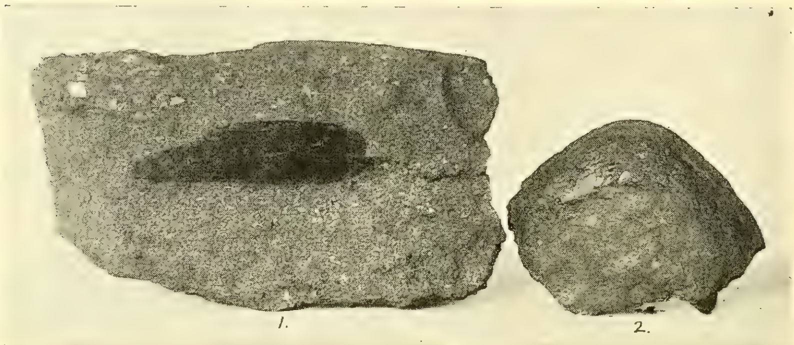

FIG. 1.—Water-worn coal pebbles occurring in coarse-grained sandstone in upper measures of Warrior Coal Field, Ala. No. 2 is a portion of a pebble 8 inches in diameter.

the coarse sand and conglomerate is very evident, and that the agent of erosion was a carboniferous stream is also evident, but whether the material now forming the coal was then in the form of chunks of coal or pieces of lignite or less carbonized wood is not apparent.

It is a well-known fact that at the present time pebbles of coal are being transported and rounded by stream action, yet the question would naturally present itself as to where the carboniferous stream could get this coal, since it is not possible that the beds of coal below could furnish it without a considerable warping and erosion of the strata prior to the period of the deposition of the coal pebbles, but such warping and erosion is not known, and even

granting such to be the case it would hardly seem possible that sufficient time would have elapsed for the coal bed some 60 feet below or even for other carbonaceous deposits still lower down in the coal measures to yield more than a lignite. It would seem to me therefore that these carbonaceous pebbles were originally transported not as a coal but as chunks of lignite or wood. It seems to me also more reasonable to conclude that they were in the form of lignite rather than in a less carbonized form, since many of the pebbles are nearly spherical and not flattened as would be expected if the pebbles were formed of wood.

Occurrences of water-worn pebbles of coal in the rock are doubtless well known to many geologists, but it has not been my pleasure to see deposits with such large pebbles elsewhere.

Reviews

An Introduction to the Geology of New South Wales. By C. A. SÜSSMILCH. Pp. 177+xii; figs. 79 and geological map. Sydney: W. A. Gullick, Government printer, 1911.

In 1909 E. F. Pittman brought out his *Epitome of the Geology of New South Wales,* which was welcomed by the geological world as giving in brief space an outline of the geologic history, so far as then known, of that interesting but far-away state. Now we are favored with a fuller and most excellent treatment of the geologic record in detail.

The earliest geologic formations in New South Wales are of limited extent. The oldest fauna yet found is the pelagic Ordovician graptolite fauna which is very poor in other forms. But in the Silurian, which is perhaps the most extensive outcropping formation in New South Wales, there is found a great wealth of fossils indicating conditions favorable to life. The Silurian was terminated and the Devonian inaugurated by pronounced deformative earth movements. In the littoral fauna, brachiopods predominated while trilobites are absent. Their absence is not easily explained, for trilobites flourished in the Silurian and are found in considerable numbers in the Carboniferous, indicating that they had not become extinct. The Devonian was closed by one of the greatest mountain-making epochs in New South Wales. Since then no part of the state, excepting the northeastern section, has been subjected to similar orogenic movements. The present elevation of the strata above sea-leavel is due to vertical uplift only.

A typical Permian formation, analogous to that of the Northern Hemisphere, does not occur in Australia, its place being taken by the so-called Permo-Carboniferous. This name has been applied in Australia to a thick series of marine and fresh-water beds which follow the Carboniferous as Süssmilch uses the term, and which in turn are overlain by fresh-water Triassic strata. An unconformity marks the division into Carboniferous and Permo-Carboniferous—a division which would seem to correspond approximately to the break between the Westphalian and Stephanian in Europe. Rather strangely, not a single member of the Carboniferous flora passed onward into the Permo-Carboniferous. The refrigeration of the climate which took place at

the beginning of the latter period, as indicated by the glacial beds in New South Wales and other parts of Australia, has been suggested as the cause of the marked break between the two floras.

Fresh-water formations characterize the Triassic and Jurassic, but a subsidence with an extensive marine transgression took place in Australia during the Cretaceous, somewhat as in the other continents. But in the Tertiary neither marine nor lacustrine deposits of any importance are known to occur; the geological formations fail to provide an adequate record of the history and much of what is known is inferred from the topographic features. The history ends tamely, for the Pleistocene glaciation in Australia was limited in extent.

Because of the definiteness with which the subject-matter is handled, the book will be extremely useful to students in far-away countries who need the larger features and the bearing of the essential facts brought out clearly but concisely. A chapter is given to each geologic period and each chapter closes with a well-considered summary which emphasizes the most significant features of that particular period. The treatment is judicious and philosophic.

R. T. C.

History of Geology. By HORACE B. WOODWARD. New York: Putnam, 1911. Pp. 204.

This little volume is included in "A History of the Sciences" series, and well accomplishes the purpose of printing a history of geology in small compass. On the whole the work has been well done, but the reader will sometimes be inclined to think that perspective has been lost through the prominence given to English geologists of the pre-observational period. The author's judgment is not always unerring, as for example in the place accorded to the bombastic and imaginative De Luc. The effect of De Luc's activity, as viewed from this distance, would seem to have been chiefly to stem the advance of independent thought by such men as Hutton and Playfair, and to lead the reactionary elements within the church.

W. H. H.

LOWER CRETACEOUS OF MARYLAND

Under the simple title *Lower Cretaceous*, the State Geological Survey of Maryland issues what is in effect a monograph of the Lower Cretaceous formations of the state and their paleontology. For while the work consists mainly of the descriptions of all the fossils hitherto found in

beds of that age in the state, a comprehensive though brief treatment of the stratigraphy, sediments, and geologic history of the formations furnishes more than a mere introduction and background for the paleontology. The volume combines the observations, experience, and knowledge of the three geologists, who more than anyone else have for many years been occupied with the study of these formations, William Bullock Clark, Arthur B. Bibbins, and Edward W. Berry.

In Maryland the Lower Cretaceous consists of three mutually unconformable formations, Patuxent, Arundel, and Patapsco, which collectively compose the Potomac group. For the benefit of those who may not have followed the progress of Atlantic Coastal Plain geology, it may be stated that no doubt is left as to the Cretaceous age of the oldest bed of the Potomac group. According to the conclusions of the authors the earliest Lower Cretaceous of the Atlantic coast in Maryland and Virginia was, after the long post-Newark hiatus, laid down in an old estuary or behind certain obstructive barriers. In this way they seem to compromise between the theory of California-gulf conditions of deposition proposed by McGee, on the one hand, and the absence of all types of marine life on the other. Account is, however, taken of the thinning of the beds to the eastward beneath the Tertiary overlap, as shown by drill records; of the fluviatile or lacustrine aspect of part of the Patuxent sediments; of the ancient forest soils and swamps of the Arundel; of the indications of differential warping, and of probable faulting near the "fall line." The average thickness of the Potomac in Maryland is between 600 and 700 feet and the average of the variable dips about 60 feet to the mile southeastward.

The Patuxent (lowest) formation, comprising a maximum thickness of 350 feet of cross-bedded sands and gravels, with some clays and kaolinized feldspar, is regarded as having been laid down in an estuary in a climate considerably warmer than that of today, within a region clothed with temperate rain forests, made up of a dense growth of ferns and cycads in more or less pure stands, with occasional conifers towering above the general level of the vegetation, which was relatively low, and gradually predominating in passing from the coast to the uplands. Growth rings in the petrified woods show seasonal changes, but the great width of the active growth ring and the narrowness as well as the irregularity of the zones of restricted growth suggest the occurrence of dry seasons rather than of frosty winters. It is certain that the winter cold was less than that of Maryland today. With the exception of one fish, the known Patuxent fossils are exclusively vegetal. They comprise

about 100 species, most of them either Jurassic survivors or of Jurassic aspect. About forty of the species do not survive the relatively short hiatus following the Patuxent.

The Arundel formation consisting typically of drab, more or less lignitic clays, carrying iron carbonate or siderite in segregations of varying forms, attains a maximum thickness of perhaps 125 feet in the middle of the belt in central Maryland, whence it thins to the seaward, with a general dip to the southeast of about 50 feet to the mile. This formation has not furnished a rich flora, but it is remarkable as the source of all the saurian vertebrates, including eight dinosaurs and one crocodile, discovered in the Potomac group. It has furnished also the three fresh-water gastropods and one of the two fresh-water pelecypods. The Arundel flora, numbering but 33 species, four only of which are not known in either of the contiguous formations, is botanically much more closely bound to the underlying Patuxent than to the Patapsco. The vertebrates of the Arundel point toward Morrison age which Professor Lull, in agreement with Williston and many other geologists, is disposed to regard as Cretaceous, at least in part. The flora is apparently bound to that of the Kootenai, also Cretaceous. According to Berry the base of the Kootenai, so far as the latter is known by its fossil plants, is slightly older than the base of the Patuxent. Berry and Lull accordingly agree that the Patuxent and Arundel formations are of Neocomian and Barremian age.

A considerable hiatus (Aptian) appears to have elapsed before the Patapsco formation, embracing over 200 feet of sands and clays, notably variegated argillaceous material, covered and even considerably transgressed the areas of the Patapsco and Arundel. Of fossil animals, a single species, *Unio patapscoensis*, has been found in this formation. However, the Patapsco flora is both interesting and important. The contrast of the flora, embracing 83 species, is marked not only by extinction of the earlier plants (including 17 ferns, 24 cycadophytes, 1 ginkgo, 12 other gymnosperms, and all of the 7 supposed primitive angiosperms) but also by the introduction of higher forms of distinctly younger aspect. For in addition to the 41 Patuxent-Arundel species which survived from the older formations there are found 42 new types, including many unquestionable angiosperms. It appears that during the interval between Arundel and Patapsco time the dicotyledons which were destined so soon greatly to outnumber the plants of all other classes in the upper Cretaceous floras had already made a good start.

The limit of space forbids even mention of the wealth of philosophical

botanical details regarding the development of the plant types, their relationships, associations, distribution, and so on. With the thoroughness characteristic of his method Berry not only describes all the species of fossil plants known from the lower Cretaceous in Maryland, but, as a basis for discussion and comparison, he summarizes all of the known lower Cretaceous floras of other parts of the world. The value of the latter treatment appears not only in his discussion of the age of the American plant beds, but in the broader correlations and in the historical outlining of the floras. His correlations show a refinement and precision that will surprise many who have not followed the recent studies of the Cretaceous floras of the Atlantic coastal plain. As already noted the Patuxent-Arundel flora, considered as a whole, is regarded by Berry as representing all but the lower portion of the Neocomian together with the Barremian. The Patapsco he correlates, on apparently good evidence, with the Albian, the Aptian of the old world being represented by the hiatus between the Arundel and the Patapsco. It may be noted in passing that a surprisingly large number of the previously recorded species of the Potomac formation fall into the ranks of synonomy as being in Berry's judgment not well founded.

Of the other well-known plant-bearing formations of the older Cretaceous in America, the Trinity is considered by Berry as representing the Aptian and the upper part of the Barremian. The Lacota formation, in the Black Hills, he views as transgressing lower on the Barremian and as falling short of the close of the Aptian, thus overlapping on both the Trinity and the Arundel, while the Fuson formation of the same region falls, he believes, within the Albian, though it is not so early as the basal portion of the latter. As already indicated, the Morrison-Kootenai beds he treats as probably Cretaceous, in which the Kootenai persisted to the close of the Barremian. On the California side the Knoxville-Horsetown beds are interpreted by him as reaching without break from the top of the Jurassic into the base of the Albian.

A map shows the distribution in Maryland of the Potomac group, the local stratigraphy and areal geology of considerable portions of which have previously been represented in greater detail in several folios of the U.S. Geological Survey.

David White

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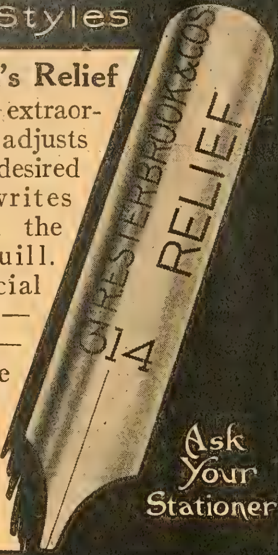

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